Control of Electrical Drives

Introductory Lecture

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1 Syllabus

2 Textbooks/References

3 Evaluation Pattern

Course Contents

Dynamics of electrical drives: Fundamental torque equations, Speed torque conventions and multiquadrant operation, Equivalent Values of drive parameters, Loads with rotational motion, Loads with translational motion, Measurement of moment of inertia, Components of load torques, Nature and classification of load torques, Calculation of time and energy-loss in transient operations, Steady state stability, Load equalisation.

Control of electrical drives: Modes of operation, Speed control and drive classifications, Closed-loop control of drives, current limit control, closed-loop torque control, speed control, speed control of multi-motor drives, speed and current sensing, phase-locked-loop (PLL) control, Closed-loop position control.

Selection of motor power rating: Thermal model of motor for heating and cooling, Classes of motor duty, Determination of motor rating, Continuous duty, Equivalent current, Torque and power methods for fluctuating and intermittent loads, Short time duty, Intermittent periodic duty, Frequency of operation of motors subjected to intermittent loads.

dc Motor drives: Starting, Braking, Speed control, Methods of armature voltage control, Ward Leonard drives, Transformer and uncontrolled rectifier control, Controlled rectifier fed dc drives, Single-phase fully-controlled and half-controlled rectifier control of dc separately excited motor, Three-phase fully-controlled and half-controlled rectifier control of dc separately excited motor, Multiquadrant operation of dc separately excited motor fed from fully-controlled rectifier, Rectifier control of dc series motor, Control of fractional hp motors, Supply harmonics, power factor and ripple in motor current, Chopper-controlled dc drives, Chopper control of separately excited dc motor and series motor, Source current harmonics in Choppers, Converter ratings and closed-loop control

Course Contents

Induction motor drives: Starting, Braking, Transient analysis, Voltage source inverter (VSI) control, Variable frequency control from a current source, Current source inverter (CSI) control, Slip power recovery, Linear induction motor and its control.

Synchronous motor and brushless dc motor drives: Synchronous motor variable speed drives, Variable frequency control, Modes of variable frequency control, Variable frequency control of multiple synchronous motors, Self-controlled synchronous motor drive employing load commutated thyristor inverter, Permanent magnet ac motor drives.

Traction drives: Electric traction services, Nature of traction load, Main line and suburban train configurations, Calculations of traction drive rating and energy consumption, Traction motors, Conventional dc and ac traction drives, 25 kV ac traction using semiconductor converter controlled dc motors, Polyphase ac motors for traction drives, dc traction employing polyphase ac motors, ac traction employing polyphase ac motors.

Textbooks/References

- Bimal K. Bose, “Modern Power Electronics and AC Drives,” *Prentice-Hall, Inc.,* 2002.
- Gopal K. Dubey, “Fundamentals of Electrical Drives”, *2nd Edition, Alpha Science International Ltd.,* 2001.
- D. W. Novotny, T. A. Lipo, “Vector Control and Dynamics of AC Drives,” *Clarendon Press,* 1996.
- R. Krishnan, “Electric Motor Drives - Modelling, Analysis and Control,” *1st Edition, Pearson Education, Inc.,* 2001.
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3 Evaluation Pattern

Evaluation Pattern

- The following is the evaluation pattern for EE 615: Control of Electrical Drives.

Description	**Weightage of Marks (M)**
Quiz-1	10
Quiz-2	10
Mid-Semester Exam	30
Quiz-3	10
Quiz-4	10
End-Semester Exam	30
Total Marks	100

Thank You

Dynamics of Electrical Drives

Lecture-1

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1 Fundamentals Torque Equations

2 Multiquadrant Operation

3 Four Quadrant Operation of a Motor Driving a Hoist Load

Introduction

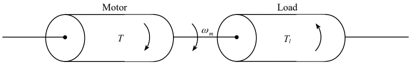

Figure 1. Equivalent motor-load system.

- A motor generally drives a load (machine) through some transmission system.
- While motor always rotates, the load may rotate or may undergo a translational motion.

Introduction

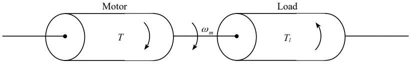

Figure 1. Equivalent motor-load system.

- A motor generally drives a load (machine) through some transmission system.
- While motor always rotates, the load may rotate or may undergo a translational motion.
- It is convenient to represent the motor load system by an equivalent rotational system.
- Here, $J \rightarrow$ moment of inertia of motor-load system referred to the motor shaft, kg-m^2.
  $\omega_m \rightarrow$ instantaneous angular velocity of motor shaft, rad/s.
  $\tau \rightarrow$ instantaneous value of developed motor torque, N-m.
  $\tau_l \rightarrow$ instantaneous value of load (resisting) torque, referred to motor shaft, N-m.

Introduction

- Load torque includes friction and windage torque of motor.
- Motor-load system is described by the following fundamental torque equation,

$$\tau - \tau_l = \frac{d}{dt}(J\,\omega_m) = J\,\frac{d\omega_m}{dt} + \omega_m\,\frac{dJ}{dt}. \tag{1}$$

- Eq. 1 is applicable to variable inertia drives such as mine winders, reel drives, and industrial robots.

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$$\tau - \tau_l = \frac{d}{dt}(J\,\omega_m) = J\,\frac{d\omega_m}{dt} + \omega_m\,\frac{dJ}{dt}. \tag{1}$$

- Eq. 1 is applicable to variable inertia drives such as mine winders, reel drives, and industrial robots.
- For drives with constant inertia, $(dJ/dt) = 0$. Therefore,

$$\tau = \tau_l + J\,\frac{d\omega_m}{dt}. \tag{2}$$

- Eq. 2 shows that torque developed by the motor is counter balanced by a load torque τ_l and a dynamic torque $J(d\omega_m/dt)$.
- Torque component $J(d\omega_m/dt)$ → dynamic torque (it is present only during the transient operation).

Introduction

- Drive accelerates or decelerates depending on whether τ is greater or less than τ_l.
- During acceleration → motor should supply not only the τ_l but an additional torque component $J(d\omega_m/dt)$ in order to overcome the drive inertia.
- In drives with large inertia (such as electric trains) τ must exceed τ_l by a large amount in order to get adequate acceleration.

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- During acceleration → motor should supply not only the τ_l but an additional torque component $J(d\omega_m/dt)$ in order to overcome the drive inertia.
- In drives with large inertia (such as electric trains) τ must exceed τ_l by a large amount in order to get adequate acceleration.
- In drives requiring fast transient response → τ should be maintained at the highest value and motor-load system should be designed with a lowest possible inertia.
- Energy associated with dynamic torque $J(d\omega_m/dt)$ is stored in the form of kinetic energy given by $J\,\omega_m^2/2$.
- During deceleration → $J(d\omega_m/dt)$ is −ve sign.
- $\therefore$ it assists the τ and maintains drive motion by extracting energy from stored kinetic energy.

Speed Torque Conventions and Multiquadrant Operation

- Multiquadrant operation of drives → useful to establish suitable conventions about the signs of torque and speed.
- Motor speed is considered +ve when rotating in the forward direction.

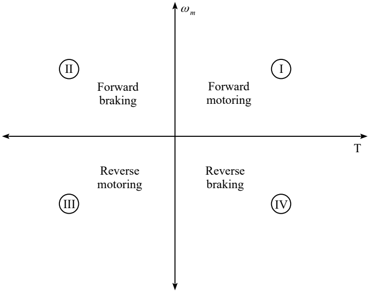

Figure 2. Multiquadrant-operation of drives.

Speed Torque Conventions and Multiquadrant Operation

- Multiquadrant operation of drives → useful to establish suitable conventions about the signs of torque and speed.
- Motor speed is considered +ve when rotating in the forward direction.
- For drives that operate only in one direction, forward speed will be their normal speed.
- In loads involving up-and-down motions, the speed of motor which causes upward motion is considered forward motion.

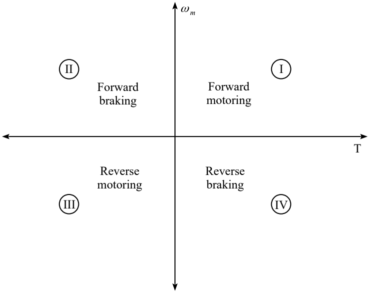

Figure 2. Multiquadrant-operation of drives.

Speed Torque Conventions and Multiquadrant Operation

- For reversible drives, forward speed is chosen arbitrarily.
- The rotation in the opposite direction → reverse speed and assigned $-$ve sign.
- Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction.

Speed Torque Conventions and Multiquadrant Operation

- For reversible drives, forward speed is chosen arbitrarily.
- The rotation in the opposite direction → reverse speed and assigned −ve sign.
- Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction.
- According to Eq. 2, +ve τ_l is opposite in direction to the +ve motor torque.
- Motor torque is considered −ve if it produces deceleration.
- Motor operates in two modes → motoring and braking.
- Motoring → converted electrical energy to mechanical energy, which supports its motion.

Speed Torque Conventions and Multiquadrant Operation

- Braking → it works as a generator converting mechanical energy to electrical energy, and thus, opposes the motion.

- Motor can provide motoring and braking operations for both forward and reverse directions.

- Power developed by a motor is given by product of speed and torque.

Speed Torque Conventions and Multiquadrant Operation

- Braking → it works as a generator converting mechanical energy to electrical energy, and thus, opposes the motion.
- Motor can provide motoring and braking operations for both forward and reverse directions.
- Power developed by a motor is given by product of speed and torque.
- In quadrant I → developed power is +ve → forward motoring.
- In quadrant II → developed power is −ve → machine works under braking opposing the motion → forward braking.
- Quadrant III and IV → reverse motoring and braking, respectively.

Four Quadrant Operation of a Motor Driving a Hoist Load

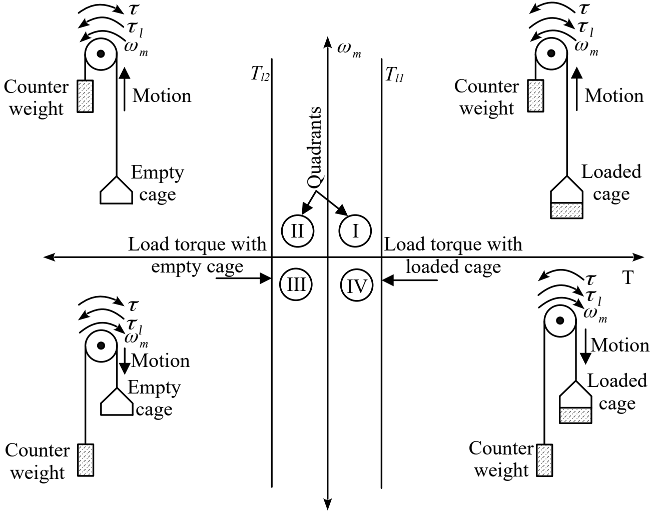

Figure 3. Four quadrant operation of a motor driving a hoist load.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Consider operation of a hoist in four quadrants as shown in Fig. 3.
- 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 man or material form one level to another level.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Consider operation of a hoist in four quadrants as shown in Fig. 3.
- 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 man or material form one level to another level.
- Other end of the rope has a counter weight.
- Here, the weight of the counter weight is chosen to be higher than the weight of an empty cage but lower than a fully loaded cage.
- Forward direction of the motor speed will be one which gives upward motion of the cage.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Load torque is shown to be constant and independent of speed.
- Gravitational torque does not change its sign even when the direction of the driving motor is reversed.
- Load torque line τ_{l1} in quadrants I and IV → speed-torque characteristics for the loaded hoist.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Load torque is shown to be constant and independent of speed.
- Gravitational torque does not change its sign even when the direction of the driving motor is reversed.
- Load torque line τ_{l1} in quadrants I and IV → speed-torque characteristics for the loaded hoist.
- This torque is the difference of torques due to loaded hoist and counter weight.
- Load torque line τ_{l2} in quadrants II and III → speed-torque characteristics for an empty hoist.
- This torque is the difference of torques due to counter weight and the empty hoist.
- Its sign is $-$ve since the weight of a counter weight is always higher than that of an empty cage.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Quadrant-I operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anticlockwise direction here.

- This motion will be obtained if the motor produces +ve torque in anticlockwise direction equal to the magnitude of τ_{l1}.

- Since the developed motor power is +ve → forward motoring operation.

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- This motion will be obtained if the motor produces +ve torque in anticlockwise direction equal to the magnitude of τ_{l1}.
- Since the developed motor power is +ve → forward motoring operation.
- Quadrant IV operation is obtained when a loaded cage is lowered.
- Since the weight of a loaded cage is higher than that of a counter weight, it is able to come down due to the gravity itself.
- To limit the speed of cage within safe value, motor must produce a +ve torque $\tau = \tau_{l2}$ in anticlockwise direction.
- As both power and speed are −ve → drive is operating in reverse braking.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Operation in quadrant II is obtained when an empty cage is moved up.
- Since a counterweight is heavier than an empty cage, it is able to pull it up.
- In order to limit the speed within a safe value, the motor must produce a braking torque equal to τ_{l2} in clockwise ($-$ve) direction. Since speed is +ve and developed power $-$ve → forward braking operation.

Four Quadrant Operation of a Motor Driving a Hoist Load

- Operation in quadrant II is obtained when an empty cage is moved up.
- Since a counterweight is heavier than an empty cage, it is able to pull it up.
- In order to limit the speed within a safe value, the motor must produce a braking torque equal to τ_{l2} in clockwise (−ve) direction. Since speed is +ve and developed power −ve → forward braking operation.
- Operation in quadrant III is obtained when an empty cage is lowered.
- Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in clockwise direction.
- Since speed is −ve and developed power +ve → reverse motoring operation.

References

- Bimal K. Bose, “Modern Power Electronics and AC Drives,” *Prentice-Hall, Inc.,* 2002.
- Gopal K. Dubey, “Fundamentals of Electrical Drives”, *2nd Edition, Alpha Science International Ltd.,* 2001.
- D. W. Novotny, T. A. Lipo, “Vector Control and Dynamics of AC Drives,” *Clarendon Press,* 1996.
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Thank You

Dynamics of Electrical Drives

Lecture-2

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Equivalent Values of Drive Parameters

- Different parts of a load → coupled through different mechanisms such as gears, V-belts and crankshaft.
- These parts have different speeds and different types of motions → rotational and translational.

Loads with Rotational Motion:

- Consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 teeth.
- Let the moment of inertia of motor and load directly coupled to its shaft be J_0, motor speed and torque of the directly coupled load be ω_m and τ_{l0}, respectively.
- Let the moment of inertia, speed and torque of the load coupled through a gear be J_1, ω_{m1} and τ_{l1}, respectively.

Loads with Rotational Motion

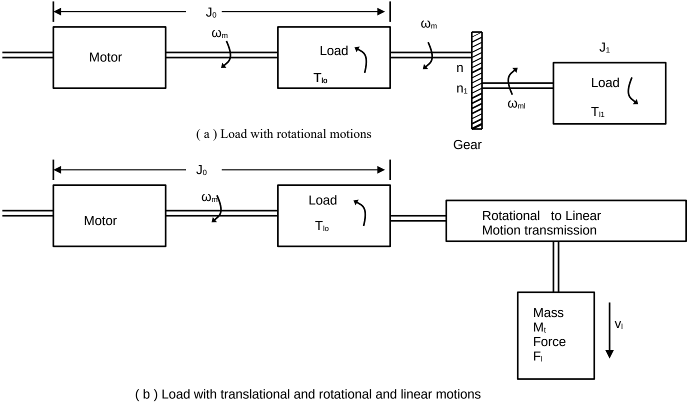


Figure 1. (a) Loads with rotational motion and (b) loads with transnational and rotational motion.

- Now,

$$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = a_1. \tag{1}$$

Where, a_1 is the gear tooth ratio.

Loads with Rotational Motion

- If the losses in transmission are neglected, then the kinetic energy due to equivalent inertia must be the same as the kinetic energy of various moving parts. Thus,

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

- From Eqs. 1 and 2,

$$J = J_0 + a_1^2 J_1. \tag{3}$$

- Power at the loads and motor must be the same. If transmission efficiency of the gears be η_1, then

$$\tau_l \omega_m = \tau_{l0} \omega_m + \frac{\tau_{l1} \omega_{m1}}{\eta_1}. \tag{4}$$

  Where, τ_l is the total equivalent torque referred to the motor shaft.

- From Eqs. 1 and 4,

$$\tau_l = \tau_{l0} + \frac{a_1 \tau_{l1}}{\eta_1}. \tag{5}$$

Loads with Rotational Motion

- If in addition to load directly coupled to the motor with inertia J_0 there are m other loads with moment of inertias J_1, J_2, ..., J_m and gear teeth ratios of a_1, a_2, ... a_m then

$$J = J_0 + a_1^2 J_1 + a_2^2 J_2 + \ldots\ldots\ldots\ldots a_m^2 J_m. \tag{6}$$

- If m loads with torques τ_{l1}, τ_{l2}, ..., τ_{lm} are coupled through gears with teeth ratios a_1, a_2, ... a_m and transmission efficiencies η_1, η_2, ..., η_m, in addition to one directly coupled, then

$$\tau_l = \tau_{l1} + \frac{a_1\,\tau_{l1}}{\eta_1} + \frac{a_2\,\tau_{l2}}{\eta_2} + \ldots\ldots\ldots + \frac{a_m\,\tau_{lm}}{\eta_m}. \tag{7}$$

- If loads are driven through a belt drive instead of gears, neglecting slippage, the equivalent inertia and torque can be obtained from Eqs. 6 and 7.

1. Loads with Rotational Motion
2. Loads with Translational Motion
3. Moment of Inertia
4. Components of Load Torques

Loads with Translational Motion

- Consider a motor driving two loads, one coupled directly to the shaft and the other through a transmission system converting rotational motion to linear motion.

- Let the moment of inertia of the motor and load directly coupled to it be J_0, τ_l directly coupled to motor be τ_{l0}, and mass, velocity and force of load with translational motion be M_1 (kg), v_1 (m/s) and F_1 (N), respectively.

- If the transmission losses are neglected, then kinetic energy due to equivalent inertia J must be the same as kinetic energy of various moving parts. Thus,

$$\frac{1}{2} J \omega_m^2 = \frac{1}{2} J_0 \omega_m^2 + \frac{1}{2} M_1 v_1^2. \tag{8}$$

or

$$J = J_0 + M_1 \left(\frac{v_1}{\omega_m} \right)^2. \tag{9}$$

Loads with Translational Motion

- ||ly, power at the motor and load should be the same, thus if efficiency of transmission be η_1

$$\tau_l\,\omega_m = \tau_{l0}\,\omega_m + \frac{F_1\,v_1}{\eta_1} \tag{10}$$

$$\tau_l = \tau_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right). \tag{11}$$

- If, in addition to one load directly coupled tot he motor shaft, there are m other loads with translational motion with velocities v_1, v_2, ...v_m and masses M_1, M_2, ...M_m, respectively, then

$$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 + M_2\left(\frac{v_2}{\omega_m}\right)^2 + \ldots\ldots + M_m\left(\frac{v_m}{\omega_m}\right)^2. \tag{12}$$

and

$$\tau_l = \tau_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) + \frac{F_2}{\eta_2}\left(\frac{v_2}{\omega_m}\right) + \ldots\ldots + \frac{F_m}{\eta_m}\left(\frac{v_m}{\omega_m}\right). \tag{13}$$

1 Loads with Rotational Motion

2 Loads with Translational Motion

3 **Moment of Inertia**

4 Components of Load Torques

Measurement of Moment of Inertia

- Moment of inertia is calculated if dimensions and weights of various parts of the load and motor are known.

- Measured experimentally → retardation test.

- In retardation test → drive runs at a speed slightly higher than rated speed and then the supply to it cut off.

- Drive continues to run due to kinetic energy stored in it and decelerates due to rotational mechanical losses.

- At any speed ω_m, power P consumed in supplying rotational losses is given by

$$P = \frac{d}{dt}\left(\frac{1}{2} J \omega_m^2\right) = J \omega_m \frac{d\omega_m}{dt}. \tag{14}$$

- From retardation test $d\omega_m/dt$ at rated speed is obtained.

Measurement of Moment of Inertia

- Now, drive is connected to the supply and run at rated speed and rotational mechanical power input P to the drive is measured.
- However, the rotational mechanical losses cannot be measured accurately since the core losses and rotational mechanical losses cannot be separated.
- Hence, the retardation test on a dc separately excited motor or a synchronous motor is carried-out with field on.
- Now, core loss is included in the rotational loss, which is the difference between armature power input and armature copper loss.
- In case of a wound rotor IM → retardation test can be carried-out by keeping the stator supply and opening the rotor winding connection.

Measurement of Moment of Inertia

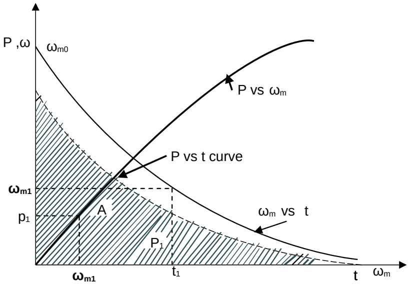


Figure 2. Graphical method of determination of the equivalent moment of inertia.

- J can be determined more accurately by obtaining the speed time curve from the retardation test and also rotational versus speed plot shown in Fig. 2.
- Using these two plots, rotational losses versus time plot can be obtained.
- Area A enclosed between the rotational loss versus t plot and the time axis (shaded area) → kinetic energy dissipated during retardation test.
- If the initial speed of the drive during retardation test is ω_{m0} then

$$\frac{1}{2} J \omega_{m0}^2 = A. \tag{15}$$

1 Loads with Rotational Motion

2 Loads with Translational Motion

3 Moment of Inertia

4 Components of Load Torques

Components of Load Torques

- Load torque $\tau_l \rightarrow$ friction torque τ_f and windage torque τ_W.
- (i) Friction torque, τ_f: Friction will be present at the motor shaft and also in various parts of the load. τ_f is equivalent value of various friction torques referred to the motor shaft.
- (ii) Windage torque, τ_W: When a motor runs, wind generates a torque opposing the motion.
- (iii) Torque required to do the useful mechanical work, τ_l: This torque depends on the particular application. It may be constant and independent of speed. It may depend on the position or path followed by load.

Components of Load Torques

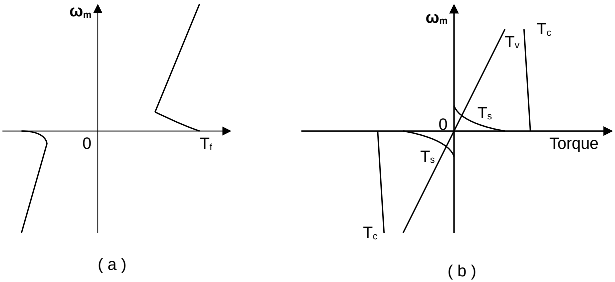


Figure 3. Friction torque and its components.

- Variation of friction torque with speed as shown in Fig. 3. Its value at standstill is much higher than its value slightly above zero speed.
- Friction at zero speed → stiction or static friction.
- Friction torque is resolved into three components.
- Component τ_V which varies lineraly with speed is called viscous friction and given as,

$$\tau_V = B\,\omega_m. \tag{16}$$

Where, B is the viscous friction coefficient.

Components of Load Torques

- Another component τ_c which is independent of speed → Coulomb friction.
- Third component τ_s accounts for additional torque present at standstill. Since τ_s is present only at standstill, it is not taken into account in the dynamic analysis.
- Windage torque τ_w is given as

$$\tau_w = C\,\omega_m^2. \tag{17}$$

Where, C is constant.

- For finite speed,

$$\tau_l = \tau_l + B\,\omega_m + \tau_c + C\,\omega_m^2. \tag{18}$$

- In many applications $\tau_c + c\,\omega_m^2$ is very small compared to $B\,\omega_m$ and neglisable compared to τ_l.
- In order to simplify the analysis, term $\tau_c + C\,\omega_m^2$ is accounted by updating the value of viscous friction coefficient B. Then,

$$\tau = J\frac{d\omega_m}{dt} + \tau_l + B\,\omega_m. \tag{19}$$

Components of Load Torques

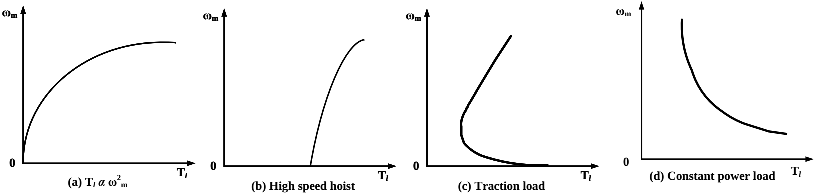
- If there is a torsional elasticity in shaft coupling the load to the motor, an additional component of load torque known as coupling torque, will be present.
- Coupling torque τ_e is given as

$$\tau_e = K_e \, \theta_e. \tag{20}$$

  Where, θ_e is the torsion angle of coupling (radians) and K_e the rotational stiffness of the shaft (N-m/rad).

- In most applications, shaft can be assumed to be perfectly stiff and τ_e can be neglected.
- There is potential energy associated with coupling torque and kinetic energy with dynamic torque.
- Exchange of energy between these two energy storage tends to produce oscillations which are damped by viscous friction torque $b \, \omega_m$.
- When B is small → oscillations occur producing noise.

Nature and Classification of Load Torques



(a) $T_l \alpha \omega^2_m$ (b) High speed hoist (c) Traction load (d) Constant power load

Figure 4. Friction torque and its components.

- A low speed hoist → torque is constant and independent of the speed.
- Paper mill drive → torque is independent of speed.
- Fans, compressors, aeroplanes, centrifugal pumps, ship-propellors, high speed hoists, traction → load torque is a function of speed.

Nature and Classification of Load Torques

- Fans, compressors, aeroplanes → windade dominates → $\tau_L \propto \omega^2$ shown in Fig. 4 (a).
- Windage is the opposition offered by air to the motion.
- Similar nature of τ_L an be expected when the motion is opposed by any other fluid, example, by water in centrifugal pumps and ship-propellors → Fig. 4 (a).
- High speed hoist → viscous friction and windage also have appreciable magnitude, in addition to gravity → Fig. 4 (b).
- Traction load → since its heavy mass, the stictiuon is large → → Fig. 4 (c).
- Torque in a coiler drive → hyperbolic in nature → Fig. 4 (d). The developed power is nearly constant at all speeds.

Nature and Classification of Load Torques

- Load torque → active and passive loads.
- Load torques which have the potential to drive the motor under equilibrium condition are called active load torques.
- Such load torques usually retain their sign when the direction of the drive rotation is changed.
- Torque due to gravitational force, tension, compression and torsion, undergone by elastic body, comes under this category.
- Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques.
- Such torques are due to friction, windage, cutting etc.

References

- Bimal K. Bose, “Modern Power Electronics and AC Drives,” *Prentice-Hall, Inc.,* 2002.
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Thank You

Dynamics of Electrical Drives

Lecture-3

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1 Time and Energy-Loss

2 Steady State Stability

Calculation of Time and Energy-Loss in Transient Operations

- Transient operations → starting, braking, speed change and speed reversal.
- The time taken and energy dissipation in motor during the transient operations can be evaluated by solving Eq. 1 along with motor circuit equations.

$$\tau = J\frac{d\omega_m}{dt} + \tau_l + B\,\omega_m. \tag{1}$$

- When τ and τ_l are constants or $\propto \omega^2$ → Eq. 1 is first order linear differential equation → can be solved analytically.
- When τ and τ_l is neither constant nor $\propto \omega^2$ → non-liner differential equation → can be solved by Runga-Kutta method.
- The transient operation is considered to be over when 95 % change in speed has taken place.
- When speed changes from ω_{m1} to $[\omega_{m1} + 0.95\,(\omega_{me} - \omega_{m1})]$ is considered to be equal to transient time.

Calculation of Time and Energy-Loss in Transient Operation

- Transient time and energy loss can also be computed with satisfactory accuracy using steady-state torque and speed-current curves of motor and speed-torque curve of load.
- This is because the mechanical time constant of a drive is usually very large compared to the electrical time constant of motor.
- Consequently, electrical transients die down very fast and motor operation can occur along the steady-state speed-torque and speed-current curves.

$$dt = \frac{J\,d\omega_m}{\tau(\omega_m) - \tau_l(\omega_m)}. \tag{2}$$

Where, $\tau(\omega_m)$ and $\tau_l(\omega_m)$ indicate that the motor and load torques are functions of drive speed ω_m.

- Time taken for drive speed to change from ω_{m1} to ω_{m2} is obtained by

$$t = J\int_{\omega_{m1}}^{\omega_{m2}} \frac{d\omega_m}{\tau(\omega_m) - \tau_l(\omega_m)}. \tag{3}$$

Calculation of Time and Energy-Loss in Transient Operation

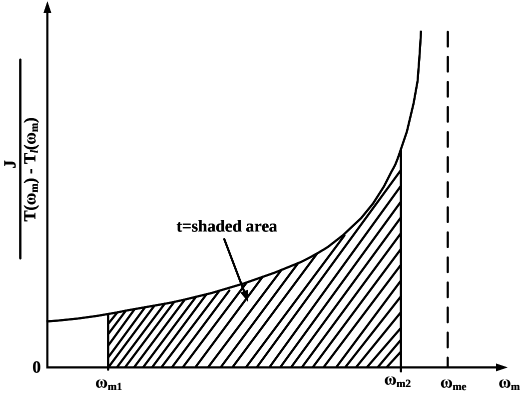

Figure 1. Friction torque and its components.

- The area between the reciprocal of the acceleration $J/[\tau(\omega_m) - \tau_l(\omega_m)]$ versus ω_m curve and ω_m-axis shown in Fig. 1.
- The transient time can be evaluated by measuring this area.

Calculation of Time and Energy-Loss in Transient Operation

- When ω_{m2} is an equilibrium speed ω_{me} → the reciprocal of acceleration will become infinite at ω_{me}.
- Consequently, time evaluated this way will be infinite.
- ∴ transient time is computed by measuring the area between speeds ω_{m1} and $\omega_{m1} + 0.95(\omega_{m2} - \omega_{m1})$.
- Energy dissipated in a motor winding during a transient operation is given by

$$E = \int_0^t R\, i^2\, dt. \tag{4}$$

  Where, R is the motor winding resistance and i is the current flowing through it.
- The area enclosed between the curve and time axis multiplied by R → gives energy dissipated in the motor winding.

1 Time and Energy-Loss

2 Steady State Stability

Steady State Stability

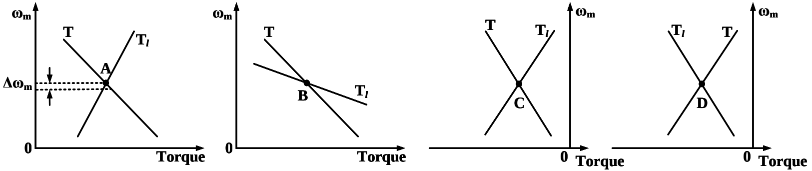

Figure 2. Friction torque and its components.

- Equilibrium speed of a motor-load system is obtained when $\tau_m = \tau_l$.
- Drive will operate in steady-state at this speed, provided it is the speed of stable equilibrium.
- In most drives, the electrical time constant of the motor is negligible compared to its mechanical time constant.
- ∴ during transient operation, motor is assumed to be in electrical equilibrium, implying that steady-state speed curves are also applicable to the transient operation.

Steady State Stability

- Steady state stability of equilibrium point A → stable, when the operation will restored to it after a small departure from it due to a disturbance in the motor or load.
- Let the disturbance cause a reduction of $\Delta \omega_m$ in speed.
- At new speed, $\tau_m > \tau_l \rightarrow$ motor will accelerate and operation will be restored to A.
- Similarly, an increase of $\Delta \omega_m$ in speed caused by a disturbance will make $\tau_l > \tau_m \rightarrow$ deceleration and restoration of operation to point A.
- Hence, the drive is steady-state stable at point A.
- Examine equilibrium point B which is obtained when the same motor drives another load.
- A decrease in speed causes the τ_l to become $> \tau_m \rightarrow$ drive decelerates and operating point moves away from B.

Steady State Stability

- Similarly, when working at B, an increase in speed will make $\tau_m < \tau_l$, which will move the operating point away from B.

- Thus, B is an unstable point of equilibrium.

- Hence, an equilibrium point will be stable when as increase in speed causes τ_l to exceed τ_m, i.e., at the equilibrium point, the following condition is satisfied.

$$\frac{d\tau_l}{d\omega_m} > \frac{d\tau}{d\omega_m}. \tag{5}$$

- Let a small perturbation in speed, $\Delta\omega_m$, results in $\Delta\,\tau$ and $\Delta\,\tau_l$ perturbations in τ and τ_l, respectively. Then,

$$(\tau + \Delta\,\tau) = (\tau_l + \Delta\,\tau_l) + J\,\frac{d(\omega_m + \Delta\omega_m)}{dt} \tag{6}$$

or

$$\tau + \Delta\,\tau = \tau_l + \Delta\,\tau_l + J\,\frac{d\omega_m}{dt} + J\,\frac{d\Delta\omega_m}{dt}. \tag{7}$$

- Substracting Eq. 1 from 11 and rearranging terms gives

$$J\,\frac{d\Delta\omega_m}{dt} = \Delta\tau - \Delta\tau_l. \tag{8}$$

Steady State Stability

- For small perturbations, the speed-torque curves of the motor and load can be assumed to be straight lines.

$$\Delta\tau = \frac{d\tau}{d\omega_m}\Delta\omega_m. \tag{9}$$

$$\Delta\tau_l = \frac{d\tau_l}{d\omega_m}\Delta\omega_m. \tag{10}$$

  Where, $d\tau/d\omega_m$ and $d\tau_l/d\omega_m$ are slopes of steady-state speed-torque curves of motor and load at operating point under consideration.

- Substituting Eqs. 9 and 10 into 8 and rearranging the terms yields

$$J\frac{d\Delta\omega_m}{dt} + \left(\frac{d\tau_l}{d\omega_m} - \frac{d\tau}{d\omega_m}\right)\Delta\omega_m = 0. \tag{11}$$

- This is a first-order linear differential equation. If the initial deviation in speed at $t = 0$ be $(\Delta\omega_m)_0$, then the solution of Eq. 11 will be

$$\Delta\omega_m = \Delta\omega_{m0}\, exp\left[-\frac{1}{J}\left(\frac{d\tau_l}{d\omega_m} - \frac{d\tau}{d\omega_m}\right)t\right]. \tag{12}$$

- An operating point will be stable when $\Delta\omega_m$ approaches zero as t approaches infinity.

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Thank You

Dynamics of Electrical Drives

Lecture-4

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Load Equalisation

- In some drive applications, τ_l fluctuates widely within short intervals of time.
- In pressing machines, a large torque of short duration is required during pressing operation. Otherwise, the torque is nearly zero.
- Electric hammer, steel rolling mills and reciprocating pumps drive → motor is required to supply peak torque demanded by load, the first motor rating has to be high.
- Secondly, the motor will draw a pulsed current from the supply.
- When the amplitude of pulsed current forms an appreciable proportion of supply line capacity, it gives rise to line voltage fluctuations, which adversely affect other loads connected to the line.
- In some applications, peak load demanded may form major proportion of the source capacity itself, as in blooming mills, then load fluctuations may also adversely affect the stability of the source.

Load Equalisation

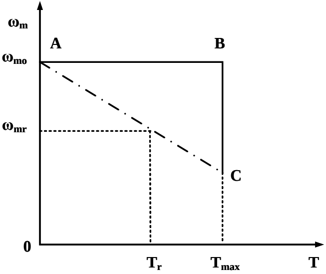

Figure 1. Shapes of motor speed torque curves for fluctuating loads.

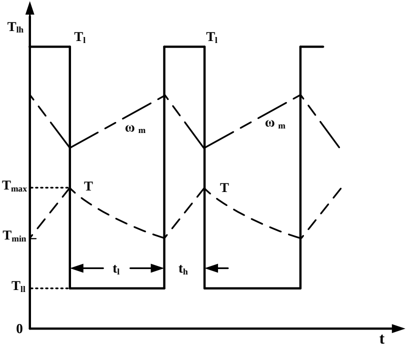

Figure 2. Variation of motor and load torques and speed for a periodic load for a drooping motor speed-curve.

Load Equalisation

- The problems of fluctuating loads are overcome by mounting a flywheel on the motor shaft in non-reversible drives.
- Motor speed-torque characteristic is made drooping (characteristic AC in Fig. 1).
- Alternatively, by closed loop current control torque is prevented from exceeding a permissible value (characteristic ABC in Fig. 1).
- During high load period, τ_l will be much larger compared to τ_m.
- Deceleration occurs, producing a large dynamic torque component ($J\, d\omega_m/dt$).
- Dynamic torque and motor torque together are able to produce torque required by the load.

Load Equalisation

- Due to deceleration, the motor speed falls.
- During light load period, τ_m exceeds the τ_l, causing acceleration and speed is brought back to the original value before the next high load period.
- Variation of motor and load torques, and speed for a periodic load and for a drooping motor speed-torque curve (AC in Fig. 1) are shown in Fig. 2.
- It shows that peak torque required from the motor has much smaller value than the peak τ_l.
- Hence, a motor with much smaller rating than peak load can be used and peak current drawn by motor from the source is reduced by a large amount.
- Fluctuations in motor torque and speed are also reduced.
- Since power drawn from the source fluctuates very little → load equalisation.

Load Equalisation

- In variable speed and reversible drives, a flywheel cannot be mounted on the motor shaft, Fig. 2 as it will increase transient time of the drive by a large amount.
- If motor is fed from a motor-generator set (Ward-Leonard Drive), then flywheel can be mounted on the shaft of the motor-generator set.
- This arrangement equalizes load on the source, but not the load on motor.
- Consequently, a motor capable of supplying peak-load torque is required.
- Moment of inertia of the flywheel required for load equalisation is calculated as follows:
- Assuming a linear motor-speed-torque curve in the region of interest (drooping characteristic AC of Fig. 1)

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{\tau_r}\tau. \tag{1}$$

Where, ω_{m0}, ω_{mr} and τ_l are no-load speed, rated speed and rated torque, respectively.

Load Equalisation

- The slow response due to large inertia, motor can be assumed to be in electrical equilibrium during transient operation of the motor-load system. In that case Eq. 1 will be

$$J\frac{d\omega_m}{dt} = -\frac{J(\omega_{mo} - \omega_{mr})}{\tau_r}\frac{d\tau}{dt} \tag{2}$$

$$J\frac{d\omega_m}{dt} = -\tau_m\frac{d\tau}{dt}. \tag{3}$$

  Where, $\tau_m = \frac{J(\omega_{mo} - \omega_{mr})}{\tau_r}$, is the mechanical time constant of the motor.

- It is the time required for the motor speed to change by $(\omega_{m0} - \omega_{mr})$ when τ_m is maintained constant at rated value τ_r.

$$\tau_m\frac{d\tau}{dt} + \tau = \tau_l. \tag{4}$$

Load Equalisation

- Consider now a periodic load torque, a cycle of which consists of one high load period with torque τ_{lh} and duration t_h and one light load period with torque τ_{ll} and duration t_l (Fig. 2).
- For high load period ($0 \leq t \leq t_h$) solution of Eq. (2.35) is

$$\tau = \tau_{lh}\,(1 - e^{-t/\tau_m}) + \tau_{min}\,e^{-t/\tau_m} \quad \text{for} \quad 0 \leq t \leq t_h. \tag{5}$$

  Where, τ_{min} is motor torque at $t = 0$, which is also the instant when heavy load τ_{lh} is applied.
- If motor torque at the end of heavy load period is τ_{max}, then from Eq.

$$\tau_{max} = \tau_{lh}\,(1 - e^{-t_h/\tau_m}) + \tau_{min}\,e^{-t_h/\tau_m}. \tag{6}$$

- Solution of Eq. 4 for the light load period ($t_h \leq t \leq t_h + t_l$) with the initial motor torque equal to T_{max} is

$$\tau = \tau_{ll}\,(1 - e^{-t^{'}/\tau_m}) + \tau_{max}\,e^{-t^{'}/\tau_m} \quad \text{for} \quad 0 \leq t^{'} \leq t_l. \tag{7}$$

  Where, $t^{'} = t - t_h$.

Load Equalisation

- When operating in steady-state, motor torque at the end of a cycle will be the same as at the beginning of the cycle.
- Hence at $t^{'} = t_l$, $\tau = \tau_{min}$. Substituting in Eq. 7 gives

$$\tau_{min} = \tau_{ll}\left(1 - e^{-t_l/\tau_m}\right) + \tau_{max}\, e^{-t_l/\tau_m}. \tag{8}$$

- Eq. 6,

$$\tau_m = \frac{t_h}{log\left(\frac{\tau_{lh} - \tau_{min}}{\tau_{lh} - \tau_{max}}\right)}. \tag{9}$$

- From $\tau_m = \frac{J(\omega_{mo} - \omega_{mr})}{\tau_r}$ and Eq. 9,

$$J = \frac{\tau_r}{\omega_{m0} - \omega_{mr}}\left[\frac{t_h}{log\left(\frac{\tau_{lh} - \tau_{min}}{\tau_{lh} - \tau_{max}}\right)}\right]. \tag{10}$$

Load Equalisation

- Also from Eq. 8,

$$\tau_m = \left[\frac{t_l}{log\left(\frac{\tau_{max} - \tau_{ll}}{\tau_{min} - \tau_{ll}}\right)} \right]. \tag{11}$$

- From $\tau_m = \frac{J(\omega_{mo} - \omega_{mr})}{\tau_r}$ and Eq. 11,

$$J = \frac{\tau_r}{\omega_{m0} - \omega_{mr}} \left[\frac{t_l}{log\left(\frac{\tau_{max} - \tau_{ll}}{\tau_{min} - \tau_{ll}}\right)} \right]. \tag{12}$$

- Moment of inertia of the flywheel required can be calculated either from Eq. 10 or 12.
- Further,

$$J = W R^2, kg - m^2. \tag{13}$$

  Where, W is the weight of the flywheel (kg) and R is the radius (m).

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Thank You

Control of Electrical Drives

Lecture-5

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1. Modes of Operation
2. Speed Control and Drive Classifications
3. Closed-Loop Control of Drives

Modes of Operation

- An electrical drive operates in three modes:
  (a) steady-state,
  (b) acceleration including starting, and
  (c) deceleration including stopping.

- According to Eq. 1,

$$\tau = \tau_l + J\frac{d\omega_m}{dt}, \tag{1}$$

  steady-state operation takes place when $\tau = \tau_l$.

- The steady-state operation for a given speed is realised by the adjustment of steady-state motor speed-torque curve such that $\tau = \tau_l$ at this speed.

- Change in speed is achieved by varying the steady-state motor speed torque curve so that τ equals τ_l at the new desired speed.

Modes of Operation

- In Fig. 1, when the motor parameters are adjusted to provide speed torque curve 1 → drive runs at the desired speed ω_{m1}.
- Speed is changed to ω_2 when the motor parameters are adjusted to provide speed-torque curve 2.
- When τ_l opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation.
- When the load is active, it can reverse its sign and act to assist the motion.

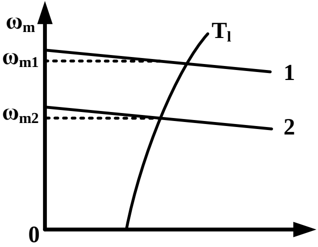

Figure 1. Principle of speed control.

Modes of Operation

- For example, when a loaded hoist is lowered or an unloaded hoist is lifted, the net load-torque acts to assist the motion.
- Steady-state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion.
- The steady state operation is obtained at a speed for which braking torque equals τ_l.
- Drive operates in quadrant II or IV depending on the direction of rotation.
- Disadvantages of mechanical braking: frequent maintenance and replacement of brake shoes, lower life, braking power is dissipated as heat.
- Electrical braking → motor is made to work as a generator converting mechanical energy to electrical energy and producing torque in a direction so as to oppose the motion.

Modes of Operation

- Even when electrical braking is employed, mechanical brakes may also be provided to ensure the reliable operation of the drive.
- Mechanical brakes → employed to hold the drive at stand-still since many braking methods are not able to produce torque at stand-still.
- Acceleration and deceleration modes → transient operations.
- Drive operates in acceleration mode whenever an increase in its speed is required.
- Hence, the motor speed-torque curve must be changed so that $\tau > \tau_l$.
- Time taken for a given change in speed → depends on the inertia of motor-load system and the amount by which τ exceeds τ_l.
- $\uparrow$ in τ is accompanied by an $\uparrow$ in motor current, i.

Modes of Operation

- Restrict i within a value that is safe for both motor and power modulator.
- In applications involving acceleration periods of long duration → current must not be allowed to exceed the rated value.
- When acceleration periods are of short duration → current higher than the rated value (is allowed during acceleration).
- In closed-loop drives requiring fast response → i may be intentionally forced to the maximum value to achieve high acceleration.
- Torque developed by an ac motor for a given current → function of motor control method employed.
- In high-performance drives, methods that produce high torque per ampere of motor current are employed.

Modes of Operation

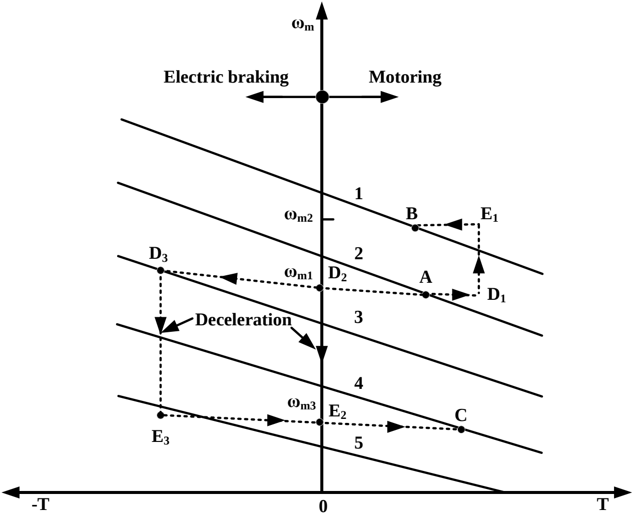

Figure 2. Speed transition paths (1 to 5 are motor speed torque curves).

Modes of Operation

- Fig. 2 shows the transition from operating point A at speed ω_{m1} to operating point B at a higher speed ω_{m2}, when τ is held constant during acceleration.
- The path consists of $A\,D_1\,E_1\,B$. In Fig. 2, 1 to 5 are motor speed-torque curves.
- Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place.
- When starting takes place at no-load or light loads → methods with low starting torque can be employed.
- When the motor must start with substantial τ_l (around rated torque) or when fast start is required → methods with high starting torque must be used.
- In applications, the motor should accelerate smoothly (without any jerk) → starting torque can be increased steplessly from its zero value → **soft start**.

Modes of Operation

- Motor operation in deceleration mode is required when a decrease in its speed is required.
- When $\tau_l > \tau \rightarrow$ deceleration occurs.
- In those applications where τ_l is always present with substantial magnitude, enough deceleration can be achieved by simply reducing τ to zero.
- In those applications where τ_l may not always have a substantial amount or where simply reducing τ to zero does not provide enough deceleration, mechanical brakes may be used to produce the required magnitude of deceleration.
- Alternatively, electric braking may be employed. Now both τ and τ_l oppose the motion, thus producing larger deceleration.
- During electric braking motor current tends to exceed the safe limit.
- When electric braking may persist for long periods, maximum current is usually restricted to the rated value.

Modes of Operation

- When electric braking occurs for short durations, maximum current is allowed to exceed the rated value.
- Higher the braking torque → greater the deceleration.
- In high-performance closed loop schemes, motor current may be intentionally forced to the maximum permissible value during deceleration.
- Figure 2 shows paths followed during transition from point A at speed ω_{m1} to a point C at a lower speed ω_{m3}.
- When deceleration is carried out using electric braking at a constant braking torque → operating point moves along the path $A\,D_3\,E_3\,C$.
- When sufficient τ_l is present or when mechanical braking is used → operation takes place along the path $A\,D_2\,E_2\,C$.

Modes of Operation

- Stopping is a special case of deceleration where the speed of a running motor is changed to zero.
- All the discussions about deceleration are applicable to stopping also.
- In applications requiring frequent, quick, accurate or rapid emergency stops, the electric braking is usually employed.
- It allows smooth and quick stops without subjecting the mechanical parts to unduly large stresses, e.g. in suburban electric trains quick stops are required.
- Use of electric braking allows a smooth stop, and increases the life of track and wheels allowing a substantial saving in cost.

Speed Control and Drive Classifications

- Drives where the driving motor runs at a nearly fixed speed → constant speed of single speed drives.
- Multi-speed drives → which operate at discrete speed settings.
- Drives needing stepless change in speed and multispeed drives → variable speed drives.
- Multi-motor drive → when a number of motors are fed from a common converter or when a load is driven by more than one motor.
- A variable speed drive is called constant torque drive → if the drive's maximum torque capability does not change with a change in speed setting.
- Constant torque → refers to the maximum torque capability of the drive and not to the actual output torque, which may vary from no load to full load torque.

Speed Control and Drive Classifications

- Ideally, for a given speed setting, the motor speed should remain constant as τ_l is changes from no load to full load.
- In practice, speed drops with an ↑ in τ_l.
- Quality of a speed control system is measured in terms of speed-regulation which is defined as

$$\text{Speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}} \times 100. \qquad (2)$$

- If open-loop control fails to provide the desired speed regulation, drive is operated as a closed-loop speed control system.

Closed-Loop Control of Drives

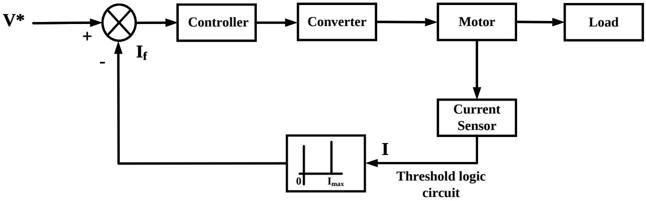

Figure 3. Block diagram of current limit control.

- Feedback loops in an electrical drive may be provided to satisfy one or more of the following requirements:
  (i) Protection
  (ii) Enhancement of speed of response
  (iii) To improve steady-state accuracy

Current-Limit Control

- Current-limit control scheme → to limit the converter and motor current below a safe limit during transient operations.
- As long as the current is within a set maximum value → feedback loop does not affect the operation of the drive.

Current-Limit Control

- During a transient operation, if current exceeds the set maximum value, the feedback loop becomes active and current is forced below the set maximum value, which causes the feedback loop to become inactive again.
- If the current exceeds set maximum value again, it is again brought below it by the action of feedback loop.
- Thus, the current fluctuates around a set maximum limit during the transient operation until the drive condition is such that the current does not have a tendency to cross the set maximum value.
- Example → during starting, current will fluctuate around the set maximum value.
- When close to the steady-state operation point, current will not have tendency to cross the maximum value.
- Consequently, the feedback loop will have no effect on the drive operation.

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Thank You

Control of Electrical Drives

Lecture-6

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1 Closed-Loop Torque Control

2 Closed-Loop Speed Control

3 Speed Sensing

4 Current Sensing

5 Phase-Locked-Loop (PLL) Control

6 Closed-Loop Position Control

Closed-Loop Torque Control

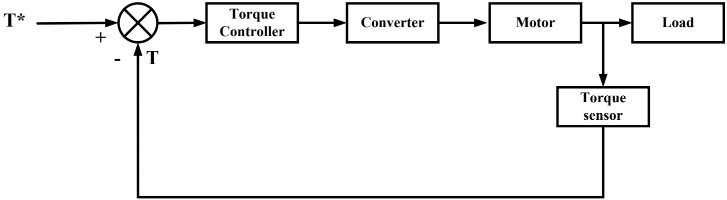

Figure 1. Block diagram of closed-loop torque control.

- Closed-loop torque control scheme → battery operated vehicles, rail cars and electric trains.
- Driver presses the accelerator to set torque reference τ^*. Through closed- loop control of torque, the actual τ follows τ^*.
- Speed feedback loop is present through the driver. By applying pressure on the accelerator, driver adjusts the speed depending on traffic, road condition, his liking, car condition and speed limit.

Closed-Loop Speed Control

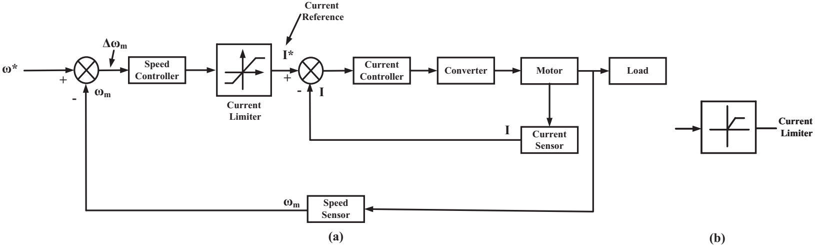

Figure 2. Block diagram of closed-loop speed control.

- Fig. 2 → closed-loop speed control scheme widely used in electrical drives.
- It employs an inner current control loop within an outer speed-loop.
- Inner current control loop is provided to limit the converter and motor current or motor torque below a safe limit.
- In some schemes, the current is controlled directly or indirectly. For example, in a variable frequency IM drives the current is controlled by controlling the slip.
- Inner current loop also reduces the effect on drive performance of any non- linearity present in converter-motor system.

Closed-Loop Speed Control Operation

- An increase in reference speed ω_m^* produce a positive error $\Delta\,\omega_m$.
- Speed error is processed through a speed controller and applied to a current limiter, which saturates even for a small speed error.
- Consequently, limiter sets the current reference for inner current control loop at a value corresponding to the maximum allowable current.
- Drive accelerates at the maximum allowable current (and in some cases τ_{max}).
- When close to the desired speed, limiter desaturates.
- Steady-state is reached at the desired speed (with some steady-state error) and at current for which $\tau = \tau_l$.
- A decrease in reference speed produces a negative speed error.
- Current limiter saturates and sets current reference for inner current loop at a value corresponding to the maximum allowable current.

Closed-Loop Speed Control Operation

- Consequently, the drive decelerates in braking mode at the maximum allowable current.
- When close to the required speed, current limiter desaturates. The operation is transferred from braking to motoring.
- Drive then settles at a desired speed and at current for which $\tau = \tau_l$.
- In those drives where the current I does not have to reverse for braking operation, current limiter will have the input-output characteristic shown in Fig. 2 (b).
- In those drive applications where τ_l is able to provide enough decelerating torque, electric braking need not be used. Then also current limiter has the characteristic shown in Fig. 2 (b).
- Current and speed controllers → proportional and integral (PI), proportional and derivative (PD) or proportional, integral and derivative (PID) controller, depending on steady-state accuracy and transient response requirements.

Speed Sensing

- Sensing of speed is required for the implementation of closed-loop speed control schemes.
- Speed is usually sensed → tachometers coupled to the motor shaft.
- A tachometer is an ac or dc generator with a high order of linearity between its speed and output voltage.
- A dc tachometer is built with a permanent magnetic field with silver brushes to reduce contact drop between brush and commutator.
- Typical voltage outputs are 10 V per 1000 rpm. The tachometer output voltage consists of a ripple whose frequency depends on its speed.
- At low speeds → adequate filtering is done by a filter with a large enough time constant to affect the dynamics of the drive.
- Special large diameter tachometers with a large number of commutator segments are sometimes built to overcome this problem.

Speed Sensing

- Tachometers are available to measure speed with an accuracy of ± 0.1 %.
- Tachometer should be coupled to the motor with a torsionally stiff coupling → natural frequency of the system consisting of rotor and tachometer lies well beyond the bandwidth of the speed control loop.
- When very high-speed accuracies are required (computer peripherals and paper mills) → digital tachometers are used.
- A digital tachometer employs a shaft encoder which gives a $f \propto \omega$.
- In dc drives, speed can be sensed without a tachometer when field current or flux is held constant, $E_b \propto \omega$.
- E_b is measured by deducting a signal equal to its armature resistance drop from motor terminal voltage.
- Method is inexpensive and provides speed measurement with an accuracy of ± 2 % of base speed.

Current Sensing

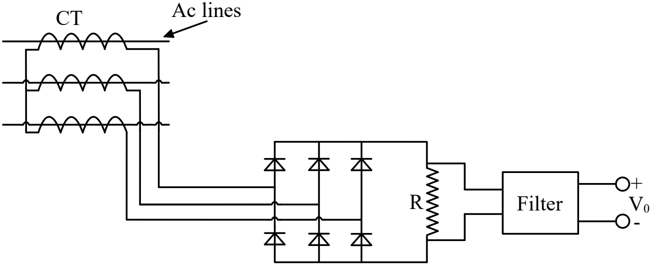

Figure 3. Sensing of current in three-phase ac lines.

- Current sensing → current limit control, inner current control loop of closed-loop speed control, closed-loop torque control of a dc drive, for sensing fault conditions, and for sensing speed in dc drives by E_b sensing method.
- To avoid interaction between control circuit (carrying low voltage and current), and power circuit (involving high voltage and current) and sometimes harmonics and voltage spikes → isolation must be provided between the two circuits.
- Current in three-phase ac circuits can be sensed using the circuit shown in Fig. 3.

Current Sensing

- Current transformers (CT) are used to provide isolation.
- The current transformer output is rectified, applied across resistor R, and filtered.
- Voltage drop $V_0 \propto$ current in ac lines.
- When used in variable frequency inverters care should be taken to avoid saturation at low frequencies.
- Major limitation of this method is that it cannot sense the phase of currents.
- In case of fully-controlled rectifiers, dc link current is $\propto$ ac line currents.
- $\therefore$ dc and ac drives fed from fully-controlled rectifier $\rightarrow$ dc link current can be sensed indirectly by sensing ac line currents of rectifier by the method of Fig. 3.

Current Sensing

Two methods are available for sensing dc current:

- (i) Use of a current sensor employing Hall-effect.
- It has the ability to sense current direction and is commercially available for a wide range of currents (few amperes to several hundred amperes) with a typical accuracy of 1 % up to 400 Hz.
- (ii) Use of a non-inductive resistance shunt in conjunction with an isolation amplifier which has an arrangement for amplification and isolation between power and control circuits.
- Limitation of shunt is that it provides only a small output voltage of the order of 7.5 to 75 mV at the rated current.
- Use of shunts of higher resistance results in increased power dissipation and drift of resistance with temperature.

Current Sensing

- In current control loop of a variable speed drive, accurate sensing of current is not necessary, and therefore, the drop across a suitable winding.
- Example: interpole winding in a dc machine is often used for current sensing.
- Isolation amplifier may consist of any one of the following circuits:
- Voltage drop across the shunt is filtered, amplified, modulated and then applied to the primary of isolation transformer.
- Output of the transformer is demodulated by a phase-sensitive demodulator filtered, buffered and applied to output terminals.
- This method allows the sensing of current direction.
- In an alternative scheme, shunt voltage drop is filtered, amplified and then processed through an opto-isolator.
- Opto-isolator output is buffered and then brought to the output terminals. Since opto-isolator gain is temperature-dependent and non-linear, two identical opto-isolator are employed in a feedback loop to compensate for these non-linearities.

Phase-Locked-Loop (PLL) Control

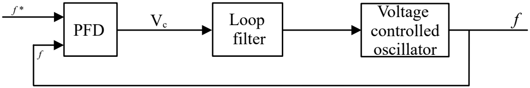

Figure 4. Block diagram of Phase-Locked-Loop (PLL).

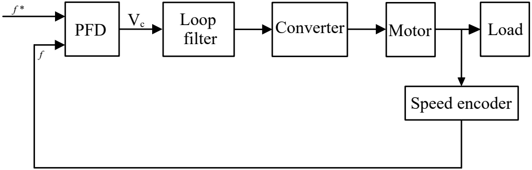

Figure 5. Block diagram of closed-loop speed control using PLL.

- Phase-Locked-Loop (PLL) → Phase frequency detector (PFD), loop filter and voltage controlled oscillator (VCO).
- A PI controller ideally should provide perfect speed regulation.
- However, due to imperfections in sensing and control circuits, the closed-loop schemes achieve a speed regulation of 0.2 %.
- PLL control → achieve a speed regulation as low as 0.002 %, which is useful in conveyers for material handling, paper and textile mills, and computer peripherals.

Phase-Locked-Loop (PLL) Control

- PLLs → inexpensive integrated circuits.
- Two pulse trains-reference pulse train of frequency f^* and the feedback pulse train of frequency f are compared in a phase detector.
- Output of the phase detector produces a pulse-width modulated output V_c.
- Pulse-width of V_c, depends on the phase difference between the two input pulse trains and polarity depends on the sign of phase difference (i.e., lag or load) between them.
- The output of the phase detector is filtered by the loop filter to obtain a dc signal and applied as control voltage to a voltage-controlled oscillator (VCO), the output is the feedback signal f.
- Since the closed-loop, VCO output frequency changes in a direction that reduces the phase difference.
- When steady state is reached, $f = f^*$ and the loop is said to have locked.

Phase-Locked-Loop (PLL) Control

- Control voltage required by VCO to produce equal to f^* comes from the phase difference between the two input signals.
- If f^* is altered, f will follow the change, and control voltage required by VCO will be obtained by the adjustment of phase difference between two input signals.
- An electrical drive employing PLL control is shown in Fig. 5.
- The VCO → replaced by converter, motor and speed encoder.
- Output of the loop-filter forms the control signal for the converter.
- It alters the converter operation such that the motor speed adjusts to make the frequency of speed encoder output signal (f) = frequency of reference signal (f^*).
- By changing f^* → motor speed can be changed.
- Main feature → excellent speed regulation.
- Disadvantages → transient response is slow, and it has a low-speed limit below which it becomes unstable.

1 Closed-Loop Torque Control

2 Closed-Loop Speed Control

3 Speed Sensing

4 Current Sensing

5 Phase-Locked-Loop (PLL) Control

6 Closed-Loop Position Control

Closed-Loop Position Control

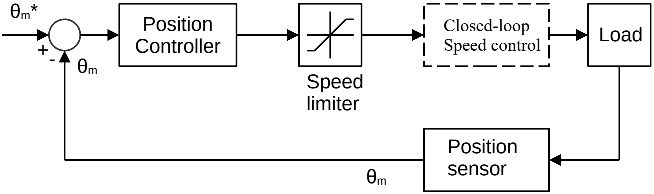

Figure 6. Block diagram of closed-loop position control.

- A closed-loop position control scheme is shown in Fig. 4.
- It consists of a closed-loop speed control system with an inner current control loop inside an outermost position loop.
- Current and speed-loop restrict the current and speed within safe limits, enhance the speed of response, reduce the effects of nonlinearities in the converter, motor and load on the transient and steady-state performance.
- Applications → feed drive in machine tools, schrew down mechanism in rolling mills.

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Thank You

Selection of Motor Power Rating

Lecture-7

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1 Selection of Motor Power Rating

2 Classes of Motor Duty

Introduction

- Machine with insufficient rating is either less reliable or fails to drive the load.
- Machine with higher power rating increases initial cost and extra energy loss when operating at lower than rated power.
- Machine experiences core loss, copper loss and friction loss.
- Losses increase machine temperature until heat outflow matches the heat generated.
- Windings are insulated from other parts of the machine. Hence, they experience higher temperature rise as compared to other parts of the machine.
- Based on temperature rise, machines are divided into classes γ, A, E, B, F, H, C.

Table 1. Insulation temperature limits

Class	**Temperature limit (°C)**
γ	90
A	105
E	120
B	130
F	155
H	180
C	Above 180

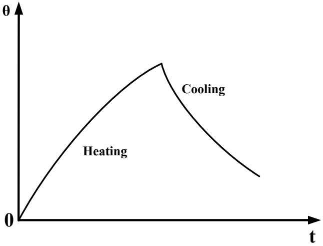

Figure 1. Heating and cooling curves.

Thermal Model of Machine I

- An electrical machine is a combination of intricate geometry and heterogenous materials.
- For simplicity, we assume an electrical machine as a homogenous body. Although inaccurate, this assumption gives a good estimate of the machine's thermal performance.
- Let the machine and the cooling medium has the following parameters at time t.
  - p_1 = Heat developed, watts.
  - p_2 = Heat dissipated to cooling medium, watts.
  - W = Weight of active parts of machine, kg.
  - h = Specific heat, Joules per kg per °C.
  - A = Cooling surface, m^2.
  - d = Coefficient of heat transfer, joules/sec/m^2/°C.
- Let the machine temperature rise by $d\theta$ during the time dt. Since,

$$\text{Heat stored in the machine} = (\text{Heat developed inside the machine} - \text{Heat dissipated to sorrounding cooling medium})$$

or

$$Whd\theta = p_1 dt - p_2 dt. \tag{1}$$

Thermal Model of Machine II

- Since $p_2 = \theta dA$, Eq.1 becomes

$$Wh\frac{d\theta}{dt} = p_1 - dA\theta. \tag{2}$$

- Where, $C = Wh$ (W/°C) is thermal capacity of machine, and $D = dA$ (watts/°C) is heat dissipation constant.
- The solution to Eq.2 is

$$\theta = \theta_{ss} + Ke^{\frac{-t}{\tau}}. \tag{3}$$

- Where, $\theta_{ss} = \frac{p_1}{dA}$ is steady state temperature, $\tau = \frac{Wh}{dA}$ is thermal time constant, and K is integration constant.
- When initial temperature is θ_1, Eq.3 becomes

$$\theta = \theta_{ss}(1 - e^{\frac{-t}{\tau}}) + \theta_1 e^{\frac{-t}{\tau}}. \tag{4}$$

- Let the load on the machine is removed at temperature θ_2 and cooling operation is started, p_1 will reduce to $p_1^{'}$ and D will increase to $D^{'}$. If time is measured from the instant load is removed, then

$$C\frac{d\theta}{dt} = p_1^{'} - D^{'}A\theta. \tag{5}$$

Thermal Model of Machine III

- The solution to Eq.4 subject to initial condition $\theta = \theta_2$ at $t = 0$ is

$$\theta = \theta_{ss}^{'}(1 - e^{\frac{-t}{\tau^{'}}}) + \theta_2 e^{\frac{-t}{\tau^{'}}}. \tag{6}$$

- If the machine is disconnected from supply while cooling, then $p_1^{'}$ and $\theta_{ss}^{'}$ is zero. Eq.5 gives

$$\theta = \theta_2 e^{\frac{-t}{\tau^{'}}}. \tag{7}$$

- Eq.4 and Eq.7 suggests that heating and cooling time constants depend on heat dissipation constant.
- In self cooled machines, the fan is mounted on motor shafts. Hence, according to the speed of the machine, the cooling time constant varies.
- Fig.1 shows the variation of motor temperature change with time during heating and cooling phase. Thermal time constants are orders of magnitude larger than electrical or mechanical time constants.

1 Selection of Motor Power Rating

2 Classes of Motor Duty

Classes of Motor Duty

Various classes of motor duty are:

- Continuous duty.
- Short time duty.
- Intermittent periodic duty.
- Intermittent periodic duty with starting.
- Intermittent periodic duty with starting and braking.
- Continuous duty with intermittent periodic loading.
- Continuous duty with starting and braking.
- Continuous duty with periodic speed changes.

Classes of Motor Duty

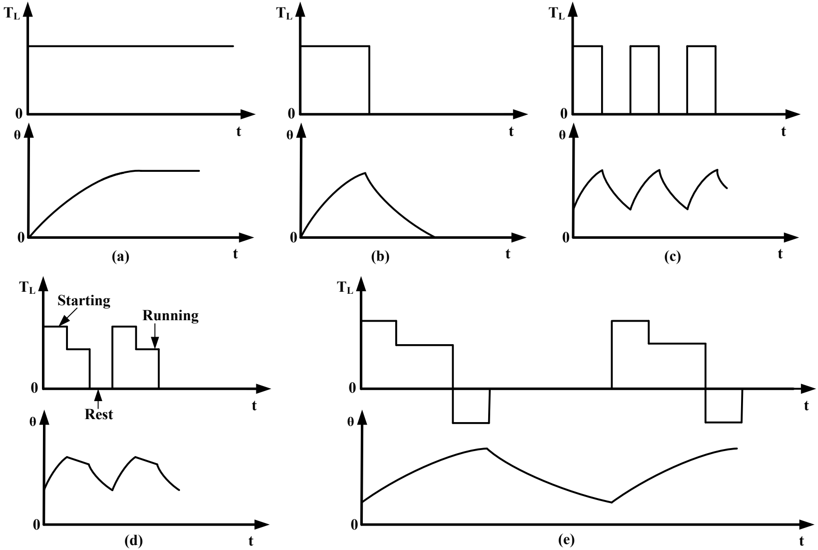

Figure 2. Some classes of motor duty.

Classes of Motor Duty

Continuous Duty [Fig. 1 (a)]:

- It denotes the motor operation at a constant load torque for a duration long enough for the motor temperature to reach steady-state value.
- This duty is characterized by a constant motor loss.
- Examples of continuous duty → paper mill drives, compressors, conveyers, centrifugal pumps and fans.

Short Time Duty [Fig. 1 (b)]:

- Time of drive operation is considerably less than the heating time constant and machine is allowed to cool off to ambinent temperature before the motor is required to operate again.
- In this operation, the machine can be overloaded until temperature at the end of loading time reaches the permissible limit.
- Examples → crane drives, drives for household appliances, turning bridges, sluice-gate drives, and valve drives.

Classes of Motor Duty

Intermittent Periodic Duty [Fig. 1 (c)]:

- It consists of periodic duty cycles, each consisting of a period of running at a constant load and a rest period.
- Neither the duration of running period is sufficient to raise the temperature to a steady-state value, nor the rest period is long enough for the machine to cool off to ambient temperature.
- Examples → pressing, cutting and drilling machine drives.

Intermittent Period Duty with Starting [Fig. 1 (d)]:

- This is intermittent periodic duty where heat losses during starting cannot be ignored.
- Thus, it consists of a period of starting, a period of operation at a constant load and a rest period with operating and rest periods being too short for the respective steady-state temperatures to be attained.
- Examples → metal cutting and drilling tool drives, drives for fork lift trucks, mine hoist etc.

Classes of Motor Duty

Intermittent Periodic duty with Starting and Braking [Fig. 1 (e)]:

- It consists of a period of starting, a period of operation with a constant load, a braking period with electrical braking and a rest period; with operating and rest periods being too short for the respective steady state temperatures to be attained.
- Examples → billet mill drive, manipulator drive, ingot buggy drive, schrewdown mechanism of blooming mill, drives for electric suburban trains and mine hoist.

Continuous Duty with Intermittent Periodic Loading:

- It consists of periodic duty cycles, each consisting of a period of running at a constant load and a period of running at no load, with normal voltage across the excitation winding.
- Again the load period and no load period being too short for the respective temperatures to be attained.
- This duty is distinguished from the intermittent periodic duty by the fact that a period of running at a constant load is followed by a period of running at no load instead of rest.
- Examples → pressing, cutting, shearing and drilling machine drives.

Classes of Motor Duty

Continuous Duty with Starting and Braking:

- Consists of periodic duty cycle, each having a period of starting, a period of running at a constant load and a period of electrical braking; there is no period of rest.
- Example → main drive of a blooming mill.

Continuous Duty with Periodic Speed Changes:

- Consists of periodic duty cycle, each having a period of running at one load and speed, and another period of running at different speed and load; again both operating periods are too short for respective steady-state temperatures to be attained.
- Further, there is no period of rest.

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Thank You

Control of Electrical Drives

Lecture-8

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Typical Parameters of an AC Compressor and Motor

Table 1. Typical Parameters of an air-conditioner compressor motor.

Parameter	Value
Rated power	1000 W
Cooling capacity	1 tonne
Rated speed	1500 rpm
Outer diameter	112 mm
Axial length	80 mm

Table 2. Fixed design parameters of the proposed hybrid PMa-SyRM.

Parameter	Value
Stator outer diameter, D_{so}	112 mm
Stator inner diameter, D_{si}	61.2 mm
Rotor outer diameter, D_{ro}	60 mm
Stack length, L_{stk}	80 mm
Air-gap thickness, g	0.6 mm

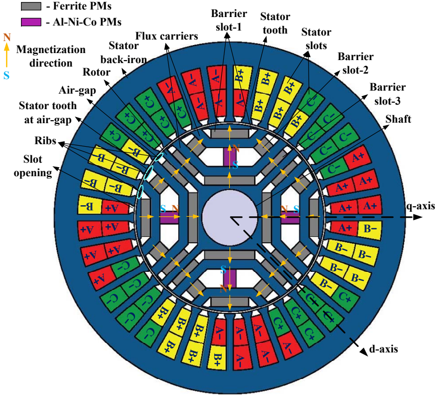


Figure 1. 2-D cross-sectional view of the proposed 36-slot, 4-pole hybrid ferrite-Al-Ni-Co PMa-SyRM.

Thermal Analysis: Model Diagram of Lumped Parameter Thermal Network

- High temperature refrigerant fluid flowing in the shaft of the motor necessitates thermal analysis.
- Thermal resistance from rotor to magnet is given as

$$R_{rm} = \frac{t_{rm}}{K_{rm} \times A_{rm}}. \tag{1}$$

  Where, t_{rm} and K_{rm} are the thickness and thermal conductivities of the air-gap imperfections between rotor to magnet, respectively. A_{rm} is the area of magnet.

- Thermal resistance from winding to stator core is given as

$$R_{wi} = \frac{t_{wi}}{K_{wi} \times A_{wi}}. \tag{2}$$

  Where, t_{wi} and K_{wi} are the thickness and thermal conductivity of the slot-liner, respectively. A_{wi} is the slot (perimeter).

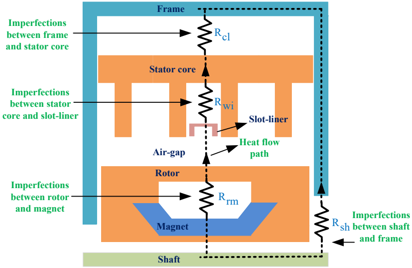


Figure 2. Model diagram of lumped parameter thermal network of the proposed hybrid PMa-SyRM.

Thermal Analysis: Model Diagram of Lumped Parameter Thermal Network

- Thermal resistance from shaft to frame and stator core to frame are given as

$$R_{sh,cl} = \frac{t_{sh,cl}}{K_{sh,cl} \times A_{sh,cl}}. \tag{3}$$

Where, t_{sh}, t_{cl}, K_{sh} and K_{cl} are the thickness and thermal conductivities of the air-gap imperfections between shaft to frame and stator core to frame, respectively. A_{sh} and A_{cl} are the end-flange and frame, respectively.

- Thermal capacitances of the magnet and winding of the motor are given as

$$C_{rm,cu} = m_{rm,cu} \times S_{rm,cu}. \tag{4}$$

Where, m is the mass and S is the specific heat of the respective material.

- Further, thermal capacitances of stator core and frame are given as

$$C_{cl,fr} = m_{cl,fr} \times S_{cl,fr}. \tag{5}$$

- The thermal parameters of the proposed hybrid PMa-SyRMs are evaluated and given in Table-3.

Thermal Analysis: Analytically Evaluated Thermal Parameters

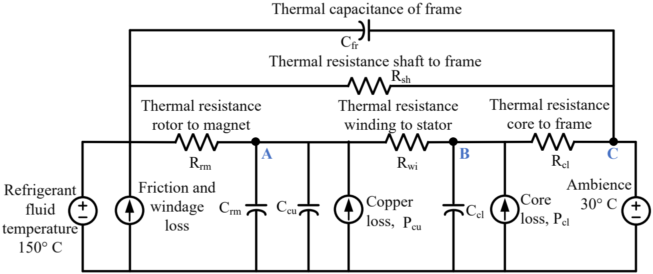
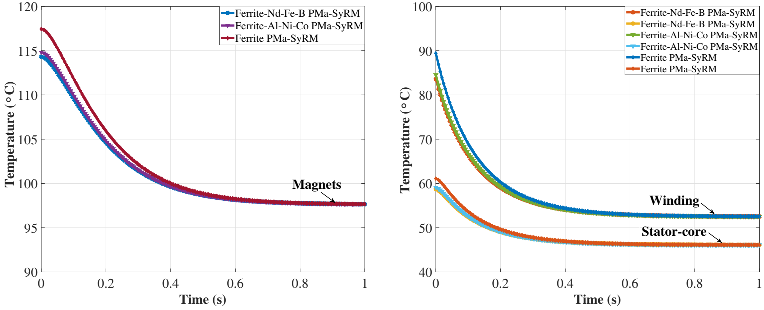


Figure 3. 1-D lumped parameter thermal network of the proposed hybrid PMa-SyRM.

Table 3. Analytically evaluated thermal parameters of the hybrid PMa-SyRMs considered for simulation in Matlab/Simulink.

Symbol	Value	Symbol	Value
R_{rm}	0.41 °C/W	t_{rm}, k_{rm}	0.1 mm, 0.031 W/(m.K)
R_{sh}	0.048 °C/W	t_{sh}, k_{sh}	0.1 mm, 0.031 W/(m.K)
R_{wi}	0.128 °C/W	t_{wi}, k_{wi}	2 mm, 0.14 W/(m.K)
R_{cl}	0.08 °C/W	t_{cl}, k_{cl}	0.1 mm, 0.026 W/(m.K)
C_{rm}	0.115 J/°C	m_{rm}, S_{rm}	1.15 kg, 0.1 J/g
C_{cu}	0.57 J/°C	m_{cu}, S_{cu}	1.5 kg, 0.383 J/g
C_{cl}	0.324 J/°C	m_{cl}, S_{cl}	3.24 kg, 0.1 J/g
C_{fr}	0.33 J/°C	m_{fr}, S_{fr}	3.3 kg, 0.1 J/g

Steady-state Temperature Rise of Hybrid PMa-SyRMs



(a) (b)

Figure 4. Temperature at (a) magnets and (b) winding and stator-core of the hybrid PMa-SyRMs obtained through the 1-D LPTN model.

- A higher temperature is obtained at t = 0 s at various motor parts since the ambient temperature is far lower than the maximum refrigerant fluid temperature (150° C).
- Steady-state temperature rise at magnets, winding and stator-core → 97°, 53° and 47° C, respectively.

Thermal 2-D FE Analysis of Hybrid PMa-SyRM

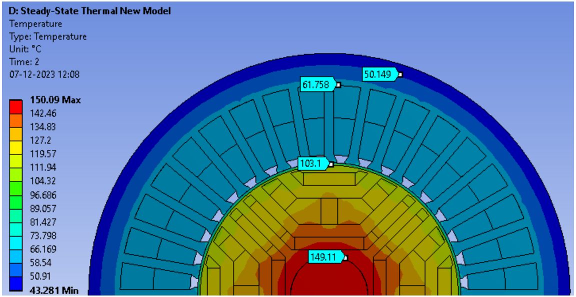


Figure 5. 2-D FE shaded temperature plot of the proposed hybrid PMa-SyRM obtained from thermal analysis.

Table 4. Analytical and 2-D FE thermal comparison of the hybrid PMa-SyRM for temperature rise of various motor parts.

Type of analysis	**Temperature at magnets in °C**	**Temperature at winding in °C**	**Temperature at stator core in °C**
Analytical	97	53	47
2-D FE	103.1	61.7	50.1

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Thank You

Selection of Motor Power Rating

Lecture-9

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1. Determination of Motor Rating
2. Short Time Duty
3. Intermittent Periodic Duty
4. Frequency of Operation of Motor Subjected to Intermittent Loads

Determination of Motor Rating

From the point of view of calculation of motor ratings, duty cycles are broadly classified into

- Continuous duty
- Fluctuating loads
- Short time and intermittent duty

Continuous Duty:

- The maximum continuous power demand of the load is ascertained.
- The selected motor should be the next higher power rating from commercially available ratings.
- The motor speed should match the load speed requirements.
- The selected motor rating should match the starting torque requirement.
- It should have the ability to drive the load during the normal disturbances coming from the supply system. This condition is generally assured by the transient and steady-state reserve torque capacity of the motor.

Equivalent current, torque and power methods for fluctuating and intermittent Loads

- This method is based on the approximation that the actual variable motor current is replaced by the equivalent I_{eq} which produces the same losses as the actual current.
- The equivalent current can be determined as follows
- Motor loss p_1 consists of two components → (i) constant loss p_c, which is independent of load which consists core loss and friction loss and (ii) load dependent copper loss.
- Therefore for fluctuating load given in fig 4.3 consists of n values of motor current $I_1, I_2, \ldots\ldots I_n$ for the durations $t_1, t_2, \ldots\ldots t_n$, respectively.
- The equivalent current I_{eq} is given by

$$p_c + I_{eq}^2 R = \frac{(p_c + I_1^2) R)t_1 + (p_c + I_2^2) R)t_2 + \ldots\ldots + (p_c + I_n^2) R)t_n}{t_1 + t_2 + \ldots\ldots\ldots + t_n}. \quad (1)$$

or

$$p_c + I_{eq}^2 R = \frac{p_c (t_1 + t_2 + \ldots\ldots\ldots + t_n)}{t_1 + t_2 + \ldots\ldots\ldots + t_n} + \frac{(I_1^2 t_1 + I_2^2 t_2 + \ldots\ldots\ldots + I_n^2 t_n) R}{t_1 + t_2 + \ldots\ldots\ldots + t_n}. \quad (2)$$

Load diagram of a Fluctuating Load

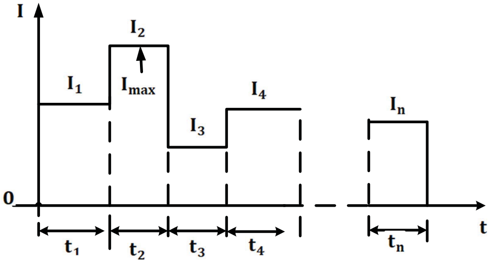

Figure 1. Load diagram of a fluctuating load.

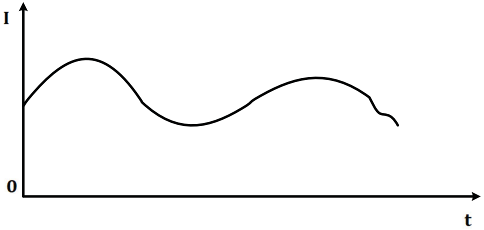

Figure 2. Load diagram of a fluctuating load.

$$I_{eq} = \sqrt{\frac{I_1^2 t_1 + I_2^2 t_2 + \ldots\ldots\ldots + I_n^2 t_n}{t_1 + t_2 + \ldots\ldots\ldots + t_n}} \tag{3}$$

- Integral $\int_0^T i^2 \, dt$ represents the area between i^2 versus t curve and the time axis for the duration 0 to T.
- The above analysis is based on the assumption that the heating and cooling remain the same.
- However, if the motor is running at constant RPM then the heating and cooling are going to be unchanged.
- If the speed varies, the constant loss will be changed marginally and if forced ventilation is used, heating and cooling can still be assumed same without the loss of much accuracy.
- In self-ventilating machines, colling conditions remain poor at low speeds.
- After I_{eq} is determined motors with next higher current rating from commercially available ratings are selected.

DC Motor

- This motor is allowed to carry the larger current than the rated current for the short duration of time.
- This condition is known as short time overload capacity of the motor.
- A normally designed dc motor is allowed to carry up to 2 times its rated current.
- Let the ratio of maximum allowable current to the rated current be denoted by λ. Then,

  $$\lambda \geq \frac{I_{max}}{I_{rated}}. \tag{4}$$

  Where, I_{max} is the ,maximum value of the current and I_{rated} is the rated current of the motor.
- If Eq. 4 is not satisfied, then the motor current rating is calculated from

  $$I_{rated} \geq \frac{I_{max}}{\lambda}. \tag{5}$$

Induction and Synchronous Motors

- For stable operation maximum load torque should be well within the breakdown torque of the motor.
- If the motor rating is selected based on Eq. 2 or 3 the the above constraint is violated.
- In the case of induction motors with normal design the ratio of breakdown to rated torque varied from 1.65 to 3, and for synchronous motors, from 2 to 2.25.
- If the ratio between breakdown to rated torque is denoted by $\lambda^{'}$, then the motor rating is based on

$$T_{rated} \geq \frac{T_{max}}{\lambda'}. \tag{6}$$

- When the load has high torque pulses selection of of motor rating based on this will be large.

- The equivalent current method assumed constant losses to remain constant for all operating points.
- $\therefore$ this method must be carefully employed when these losses vary.
- This method is also not applicable to the frequency-dependent parameters in the equivalent circuit.
- For example, in deep bar and double squirrel cage rotor motors the rotor winding resistance and reactance vary widely during starting and braking making this method inapplicable.
- When the torque is directly proportional to the current like dc separately excited motor the from Eq. 2

$$T_{eq} = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + \dots\dots\dots + T_n^2 t_n}{t_1 + t_2 + \dots\dots\dots + t_n}}. \tag{7}$$

- Eq. 7 can be employed to directly ascertain the motor torque rating.
- When the motor operates at nearly fixed speed its power will be $\propto$ torque; hence, for nearly constant speed operation, the power rating of the motor can be directly from,

$$P_{eq} = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \dots\dots\dots + P_n^2 t_n}{t_1 + t_2 + \dots\dots\dots + t_n}}. \tag{8}$$

Short Time Duty

- In short time duty, time of motor operation is considerably less than the heating time constant and motor is allowed to cool down to the ambient temperature before it is required to operate again.

- If a motor with a continuous duty power rating of P_r is subjected to a short time duty load of magnitude P_r then the motor temperature rise will be far below the maximum permissible value theta per and the motor will be highly underutilized.

- $\therefore$ motor can be overloaded by a factor K (K > 1) such that the maximum temperature rise just reaches the permissible value θ_{per}.

- When the duration of the running period in a duty cycle with power $K\,P_r$ is t_r then from $\theta = \theta_{ss}\left(1 - e^{-t/\tau}\right) + \theta_1\,e^{-t/\tau}$.

Short Time Duty

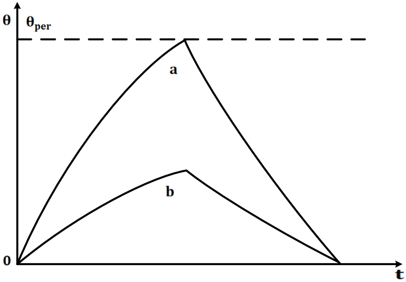

Figure 3. θ versus t curves for short time duty loads.

$$\theta_{per} = \theta_{ss}(1 - e^{\frac{-t_r}{\tau}}), \tag{9}$$

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{1}{1 - e^{\frac{-t_r}{\tau}}}. \tag{10}$$

- Note that θ_{ss} is the steady state temperature rise which will be attained if motor delivers a power (KP_r) on continuous basis, whereas the permissible temperature rise θ_{per} is also the steady state temperature rise attained when motor operates with a power P_r on continuous basis.
- The motor losses for powers P_r and (KP_r) be P_{1r} and P_{1s}, respectively.

Short Time Duty

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{p_{1s}}{p_{1r}} = \frac{1}{1 - e^{\frac{-t_r}{\tau}}}. \tag{11}$$

Let,

$$p_{1r} = p_c + p_{cu} = p_{cu}(\alpha + 1), \tag{12}$$

Where,

$$\alpha = \frac{p_c}{p_{cu}}. \tag{13}$$

p_c is the load independent (constant) loss and p_{cu} is the load dependent loss. Then

$$p_{1s} = p_c + p_{cu} \times (\frac{KP_r}{P_r})^2 = p_c + K^2 p_{cu}. \tag{14}$$

Substituting from Eq. 13

$$p_{1s} = p_{cu} \times (\alpha + K^2). \tag{15}$$

Substituting from Eqs. 12 and 15 into Eq. 11 gives

$$\frac{\left(\alpha + K^2\right)}{(\alpha + 1)} = \frac{1}{\left(1 - e^{\frac{-t_r}{\tau}}\right)} \tag{16}$$

Short Time Duty

$$K = \sqrt{\frac{1+\alpha}{1-e^{\frac{-t_r}{\tau}}} - \alpha}. \tag{17}$$

- Eq. 17 allows the calculation of overloading factor K, which can be calculated when constant and copper losses are known separately.
- When separately not known, total loss is assumed to be only proportional to $(\text{power})^2$, i.e., α is assumed to be 0.
- K is subjected to the constraints imposed by maximum allowable current in case of dc motors and breakdown torque limitations in case of induction and synchronous motors.

Intermittent Periodic Duty

- Consider a simple intermittent load, where the motor is alternatively subjected to a fixed magnitude load $P_r^{'}$ of duration t_r and standstill condition of duration t_s.
- As the motor is subjected to a periodic load, after the thermal steady state is reached the temperature rise will fluctuate between a maximum value θ_{max}, and a minimum value minimum value θ_{max}.
- For this load, the motor rating should be selected such that $\theta_{max} \leq \theta_{per}$, where θ_{per} is the maximum permissible temperature rise of the motor.
- The temperature at the end of the working (or running) interval will be given by

$$\theta_{max} = \theta_{ss} \left(1 - e^{\frac{t_r}{\tau_r}}\right) + \theta_{min} \, e^{-\frac{t_r}{\tau_r}} \tag{18}$$

Intermittent Periodic Duty

- Fall in temperature rise at the end of standstill interval t_s will be

$$\theta_{min} = \theta_{max}\, e^{-\frac{t_s}{\tau_s}}. \qquad (19)$$

Where, τ_r and τ_s are the thermal time constants of motor for working and standstill intervals.

- Combining Eqs. 18 and 19 yields,

$$\frac{\theta_{ss}}{\theta_{max}} = \frac{1 - e^{-[(t_r/\tau_r)+(t_s/\tau_s)]}}{1 - e^{-t_r/\tau_r}} \qquad (20)$$

- For full utilization of the motor, $\theta_{max} = \theta_{per}$.

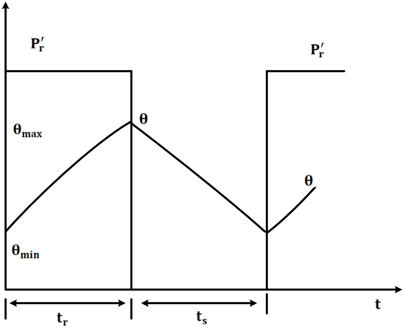

Figure 4. Intermittent periodic load.

Intermittent Periodic Duty

- Further θ_{per} will be the motor temperature rise when it is subjected to its continuous rated power P_r.
- The ratio θ_{ss}/θ_{max} will be proportional to losses that would take place for two values of load. If losses for load values P_r and P_r' be denoted by p_{1r} and p_{1s} then

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{p_{1s}}{p_{1r}}. \tag{21}$$

- The overloading factor $K(= P_r'/P_r)$ is given by

$$K = \sqrt{(\alpha + 1)\frac{1 - e^{-[(t_r/\tau_r)+(t_s/\tau_s)]}}{1 - e^{(-t_r/\tau_r)}} - \alpha} \tag{22}$$

- K can be determined from Eq. 22 subject to the maximum current limitation of dc motors and breakdown torque constraints of induction and synchronous motors.
- When constant and copper losses are not available separately, α is replaced by zero in Eq. 22.

1. Determination of Motor Rating
2. Short Time Duty
3. Intermittent Periodic Duty
4. Frequency of Operation of Motor Subjected to Intermittent Loads

Frequency of Operation of Motor Subjected to Intermittent Loads

- In applications where a motor is started and stopped frequently, it is required to determine the maximum number of switching permissible per hour.
- In such cases, usually the time taken for starting and breaking operation are comparable to running time, and t_r and t_s are very small to τ_r and τ_s, respectively.
- Let us examine the intermittent load of Fig. further. Since e^{-x} can be approximated by (1-x) when x is very small.

$$\frac{p_{1s}}{p_{1r}}\left(\frac{t_r}{\tau_r}\right)=\left(\frac{t_r}{\tau_r}+\frac{t_s}{\tau_s}\right). \tag{23}$$

$$p_{1s}t_r=p_{1r}t_r+p_{1r}\left(\frac{\tau_r}{\tau_s}t_s\right). \tag{24}$$

- L.H.S of Eq. (24) represent the total loss of energy in each cycle of the intermittent load of Fig. 4.
- R.H.S of equation can be considered to represent the amount of energy dissipated per cycle; rate of dissipation per second being p_{1r} during the running interval and $p_{1r}(\frac{\tau_r}{\tau_s})$ during the period of standstill.

Selection of Motor Power Rating

- Thus Eq. 24. provides energy balance relation when the period of intermittent loading is very small, compared to the thermal time constants of the machine.
- Applying relationship of Eq. 24 to intermittent loads with frequency starting and braking, and short running intervals yields

$$E_s + p_{1s}t_r + E_b = p_{1r}(\gamma t_{st} + t_r + \gamma t_b + \beta t_s). \qquad (25)$$

Where, E_s = loss of energy during starting.
E_b = loss of energy during braking.
p_{1s} = loss of power during running interval.
p_{1r} = rated loss of power of the motor.
t_r = length of the running interval.
t_{st} = length of the starting interval.
t_b = length of breaking interval.
t_s = length of standstill interval.
γ and β are numerical constants based on measurements.
β varies between 0.3 and 0.7.

Selection of Motor Power Rating

- The value of γ is assumed as $\gamma = \frac{1+\beta}{2}$, and the speed changes from zero to running value during starting and braking, the speed changes from zero to running value.
- $\therefore$ effective dissipation factor can be considered as the mean of those at running and standstill conditions.
- t_s is calculated from Eq. 25. Then, the permissible frequency of switching per hour is

$$f_{max} = \frac{3600}{t_{st} + t_r + t_b + t_s} \tag{26}$$

- Eqs. 25 and 26 suggest that the switching frequency can be increased by reducing loss during starting, braking and running by use of efficient method of control, and by improving heat dissipation by use of forced ventilation.
- The most efficient methods of control for dc and ac motors are armature voltage control and variable frequency control, respectively.

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Thank You

dc Motor Drives

Lecture-10

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1 Starting

2 Braking

3 Speed Control

Starting

- Maximum current that a dc motor can safely carry during starting is limited by the maximum current that can be commutated without sparking.
- For normally designed machines → twice the rated current can be allowed to flow, and for specially designed machines → 3.5 times.
- At standstill, E_b is zero and the only resistance opposing flow of current is R_a, which is quite small for all types of dc motors.
- If a dc motor is started with full supply voltage → high current will flow → heavy sparking at the commutator and heating of the winding.
- $\therefore$ it is necessary to limit the current to a safe value during starting.
- When motor speed is controlled by armature voltage control → controller controls the speed, which is used for limiting motor I during starting to a safe value.

Starting

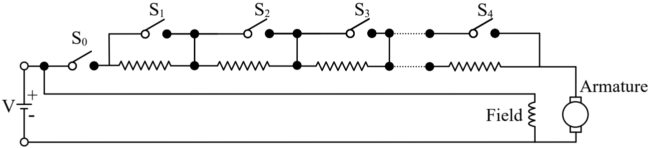


Figure 1. Starting of a dc shunt motor.

- In the absence of such a controller, a variable resistance controller is used for starting as shown in Fig. 1.
- As the motor accelerates and E_b rises, one section of the resistor is cut out at a time (either manually or automatically with the help of contactors).
- Such that current is kept within specified maximum and minimum values (Fig. 2).

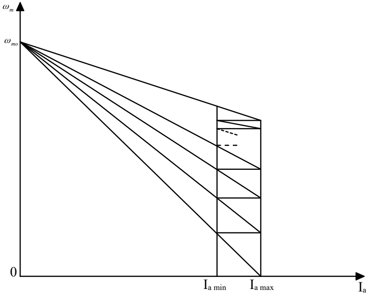


Figure 2. Speed versus armature current characteristics during starting of a dc shunt motor.

1 Starting

2 Braking
- Regenerative Braking
- Dynamic Braking
- Plugging

3 Speed Control

Braking

- In braking, the motor works as a generator developing a negative torque which opposes the motion.
- Three types of braking → (i) regenerative braking, (ii) dynamic or rheostatic braking and (iii) plugging or reverse voltage braking.

Regenerative Braking

- In regenerative braking, generated energy is supplied to the source.
- The following condition should be satisfied

$$E > V \quad \text{and negative } I_a \tag{1}$$

- Field flux cannot be increased substantially beyond rated because of saturation.
- For a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated and with a variable voltage source it is also possible below rated speeds.

Regenerative Braking

- The speed-torque characteristics are shown in Fig. 3 for a separately excited motor.
- In series motor as speed ↑s → I_a, and therefore, flux ↓s.
- Consequently, condition of Eq. 1 cannot be achieved. Thus, regenerative braking is not possible.
- In actual supply system when the machine regenerates its terminal voltage rises.
- Consequently, the regenerated power flows into the loads connected to the supply and the source is relieved from supplying this amount of power.

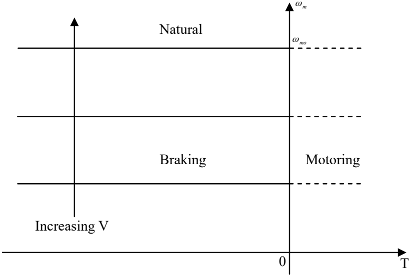


Figure 3. Regenerative braking characteristics of a separately excited motor.

Regenerative Braking

- Regenerative braking is possible → only when there are loads connected to the line, and they are in need of power more are equal to the regenerated power.
- When the capacity of the loads is less than the regenerated power → all the regenerated power will not be absorbed by the loads.
- The remaining power will be supplied to capacitors (including stray capacitances) in line and the line voltage will rise to dangerous values leading to insulation breakdown.
- Hence, regenerative braking should only be used when there are enough loads to absorb the regenerated power.
- Alternatively, an arrangement is made to divert the excess power to a resistance bank where it is dissipated as heat.
- Such braking → composite braking, since it is a combination of regenerative braking and dynamic braking.
- When the source is a battery, the regenerated energy can be stored in the battery.

Dynamic Braking

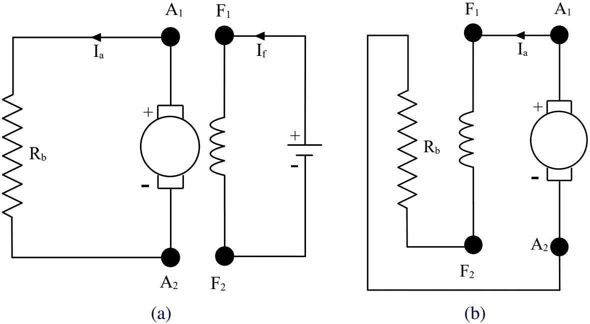
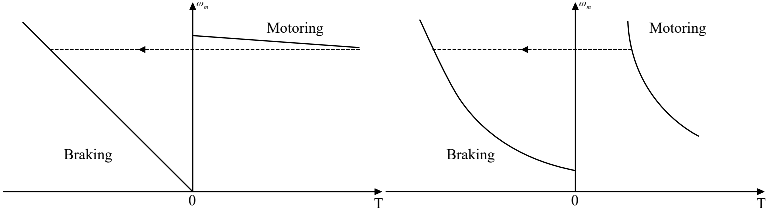


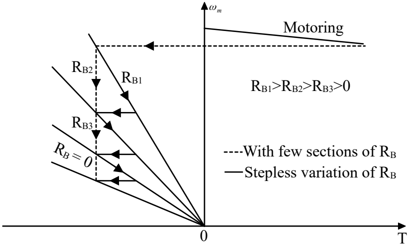
Figure 4. Dynamic braking of (a) dc separately excited motor and (b) series motor.

- Dynamic braking → motor armature is disconnected from the source and connected across a resistance R_B.
- The generated energy is dissipated in R_B and R_a.
- Braking connections are shown in Fig. 4 (a) and (b), respectively.

Dynamic Braking



(a) dc separately excited motor (b) series motor



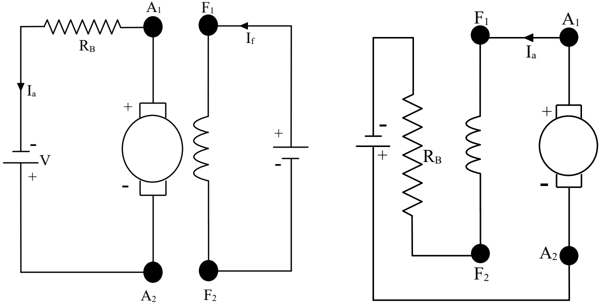
(c) Separately excited motor with variable R_a

Figure 5. Dynamic braking speed-torque curves.

Dynamic Braking

- Since series machine works as a self-excited generator, the field connection is reversed so that the field assists the residual magnetism.
- Fig. 5 (a) and (b) → speed-torque curves and transition from motoring to braking.
- When fast braking is desired → R_B consists of a few sections.
- As the speed falls, sections are cut-out to maintain a high average torque, as shown in Fig. 5 (c) for a separately excited motor.
- During braking, a separately excited motor can be converted as a self-excited generator. This permits braking even when the supply fails.

Plugging

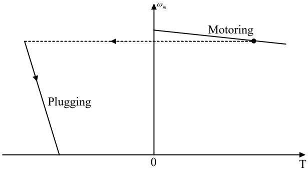


(a) dc separately excited motor (b) series motor

Figure 6. Plugging operation of dc motors.

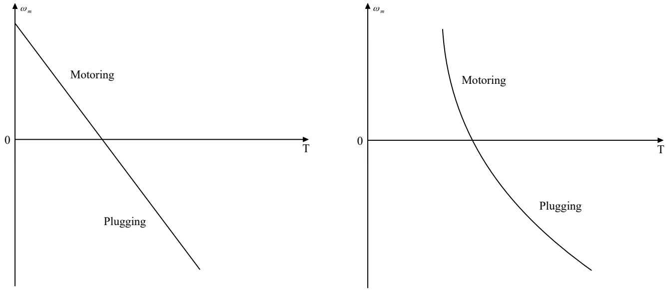
- For plugging, the supply voltage of a separately excited motor is reversed so that it assists E_b in forcing I_a in the reverse direction (Fig. 6).
- A resistance R_B is also connected in series with armature to limit the current.
- For plugging of a series motor, armature alone is reversed. Speed-torque curves are shown in Fig. 7.

Plugging



(a) dc separately excited motor (b) series motor

Figure 7. Plugging speed-torque curves of (a) dc separately excited motor and (b) series motor.



(a) dc separately excited motor (b) series motor

Figure 8. Counter-torque braking of (a) dc separately excited motor and (b) series motor.

Plugging

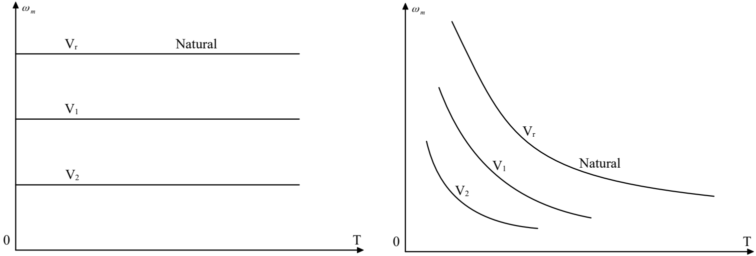
- Plugging for motor rotation in reverse direction arises → when a motor connected for forward motoring, is driven by an active load in the reverse direction.
- Here again, E_b and V act in the same direction. However, the direction of torque remains positive (Fig. 8).
- This type of situation arises in crane and hoist applications and the braking → counter-torque braking.
- Plugging gives fast braking due to high average torque, even with one section of braking resistance R_B.
- Since T is not zero at $\omega_m = 0$, when used for stopping a load, the supply must be disconnected when close to zero speed.
- Centrifugal switches are employed to disconnect the supply.
- Plugging is highly inefficient → in addition to the generated power, the power supplied by the source is also wasted in resistances.

1 Starting

2 Braking

3 Speed Control

Speed Control

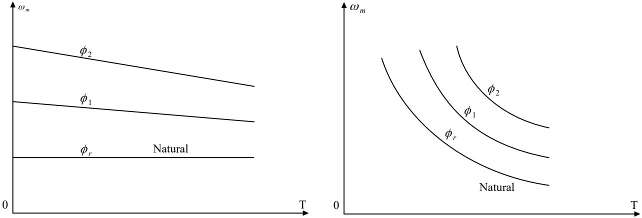


(a) dc separately excited motor (b) series motor

Figure 9. Armature voltage control $V_r > V_1 > V_2$.

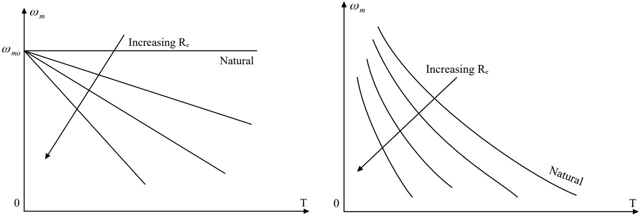
- Speed control → (i) armature voltage control, (ii) field flux control and (iii) armature resistance control.
- Armature voltage control is preferred → high η, good transient response and good speed regulation.
- It provides speed control below base speed (rated speed) since the armature voltage cannot be allowed to exceed the rated voltage.

Speed Control



(a) dc separately excited motor (b) series motor

Figure 10. Field flux control $\phi_r > \phi_1 > \phi_2$.



(a) dc separately excited motor (b) series motor

Figure 11. Speed torque curves of dc motors with resistance control (R_e: external resistance).

Speed Control

- For speed control above base speed → field flux control is employed.
- In a normally designed motor, the maximum speed can be allowed up to twice rated speed and in specially designed machines it can be six times rated speed.
- Maximum torque and power limitations of dc drives operating with armature voltage control and full field below rated speed and flux control at rated armature voltage above rated speed are shown in Fig. 12.
- In armature voltage control at full field, $T \propto I_a$ consequently, the maximum torque that the machine can deliver has a constant value.
- In the field control at rated armature voltage, $P_m \propto I_a$ (since $E \approx V =$ constant).
- $\therefore$ maximum power developed by the motor has a constant value.

Speed Control

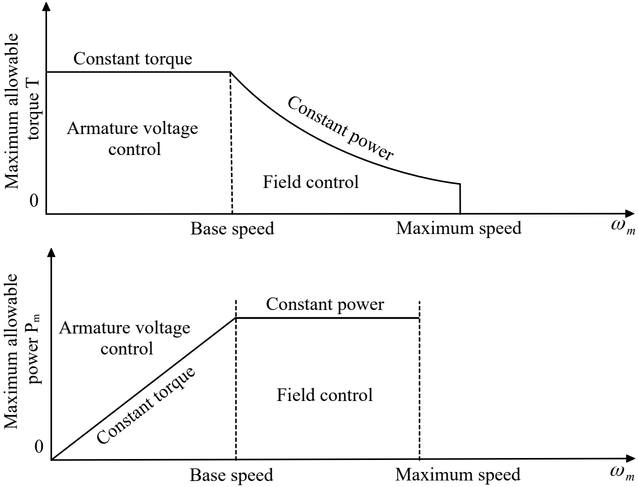


Figure 12. Torque and power limitations in combined armature voltage and field control.

Speed Control

- Separately excited motor → flux is controlled by varying V_{field}.
- Series motor → flux is controlled either by varying the number of turns in the field winding or connecting a diverter resistance across the field winding.
- In armature resistance control, speed is varied by wasting power in external resistors that are connected in series with the armature.
- Since it is an inefficient method of speed control, it was used in intermittent load applications where the duration of low-speed operation forms only a small proportion of total running time (for example, traction).
- It has, however, been replaced by armature voltage control in all these applications.

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Thank You

dc Motor Drives

Lecture-11

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Introduction

Variable armature voltage for speed control, starting, braking and reversing of dc motors can be obtained by the following methods:

When the supply is *ac*

- Ward-Leonard schemes.
- Transformer with taps and an uncontrolled rectifier bridge.
- Static Ward-Leonard scheme or controlled rectifiers.

When the supply is *dc*

- Chopper control.

Chopper control can also allow a stepless variable resistance to be obtained from a fixed resistance for dynamic braking of dc motors.

Ward Leonard Drives

- Ward Leonard Drive → consists of a separately excited generator feeding the dc motor to be controlled.
- The generator is driven at a constant speed by an ac motor connected to 50 Hz ac mains.
- The driving motor may be an induction or a synchronous.
- When the source of power is not electrical, generator is driven by a non-electrical prime mover such as diesel engine or gas turbine.
- While the dc motor may be driven at low speeds → high torque and relatively large frame size, generator being of the same voltage, current and power ratings as the motor can run at a higher speed with a view to reduce its cost and size.
- Motor terminal voltage is controlled by adjusting the I_f of the generator.
- When field winding voltage is smoothly varied in either direction, the motor V_t and therefore, speed can be steplessly varied from full +ve to full −ve.

Ward Leonard Drives

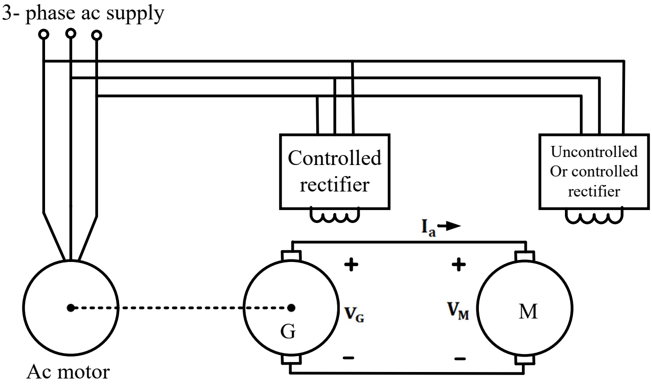

Figure 1. Block-diagram of Ward-Leonard drive.

Ward Leonard Drives

- Feature of this drive → inherent ability for regenerative braking down to very low motor speed.
- This combined with the variation of armature voltage in either direction, allows efficient operation of the drive in all four quadrants of speed-torque plane.
- For regenerative braking, the output voltage of generator G is reduced below the induced voltage of motor M by decreasing the generator I_f.
- This reverses the current flowing through the armatures of machines G and M.
- Now machine M works as a generator and G as a motor.
- Mechanical energy provided to machine M, either from the kinetic energy of rotating parts or due to an active load acting on its shaft, is converted into electrical energy.
- Electrical energy supplied by Machine M is converted into mechanical energy by machine G.
- The ac motor, which now works as a generator, converts the mechanical energy to electrical energy and feeds it to the ac source.

Ward Leonard Drives

- Control of generator field is obtained by rheostats when low ratings are involved and closed-loop control is not desired.
- Power requirement of the rheostats → order 1 to 2 % of the total input to the motor.
- For higher power applications or for closed-loop control, the field is supplied by a power amplifier consisting of a controlled rectifier, chopper or transistor amplifier.
- Old installations may use a magnetic amplifier or amplidyne.
- For reversible drives, a power amplifier capable of supplying controlled field current in either direction is required.
- It may, therefore, consists of a single-phase or three-phase dual converter, four-quadrant chopper or four-quadrant transistor amplifier.
- When the drive operates only in one direction, a power amplifier capable of supplying controlled field current only in one direction is used in order to reduce cost.
- The power amplifier may then consists of a half-controlled rectifier, step-down chopper or one quadrant transistor amplifier.
- In this case the field current can only be reduced to zero, but cannot be reversed.

Ward Leonard Drives

- When the field is controlled by a power amplifier capable of supplying current only in one direction, the minimum speed obtainable is of the order 0.1 of base speed.
- This limit on the minimum value of speed is imposed because of the residual magnetism of generator field.
- Due to residual magnetism, even when field current is zero, enough voltage is generated to make the motor crawl particularly when the load is light.
- To prevent crawling and to reduce the motor speed to zero, following three methods are employed: (a) armature circuit is opened.
- (b) A differential field winding on the generator is connected across the armature terminals.
- Such a field will oppose the residual flux, and although it will not reduce the residual voltage to zero, it will prevent build-up of a large circulating current.
- (c) The field winding of generator is connected across armature terminals such that the current through it produces mmf which opposes the residual mmf.
- This type of connection is commonly known as suicide connection.

Ward Leonard Drives

- The nature of speed-torque characteristics is similar to that of separately excited dc motors.
- Drop in motor speed due to change in load torque is caused by the drop of voltage across the R_a of the two machines.
- When motor speed, and therefore, generator output voltage is high, armature circuit resistance drop is only a small percentage of generator output voltage.
- $\therefore$ percentage speed regulation of the motor is good.
- At low speed, the R_a drop forms a large percentage of generator output voltage.
- This makes the percentage speed regulation not only large, the motor may stall with even a slight increase in load torque.
- When speed control in wide range is required, control of generator output voltage is combined with motor field control.
- Speeds below and above base speed are obtained by armature voltage control and motor field control, respectively.
- The maximum speed obtainable by motor field control is limited to twice base speed for normally designed and six times for specially designed motors.

Ward Leonard Drives

- Combination of field control with armature voltage control permits the ratio of maximum to minimum available speeds to be 20 to 40.
- With closed-loop control, the range can be extended further and can be realised up to 200.
- When field control is required, the motor field is fed from a half-controlled rectifier, step-down chopper or a single quadrant transistor amplifier.
- When not required motor field is fed from an uncontrolled rectifier.
- For low-power applications a resistance may be connected in series with the field.
- ac motor can be an induction or a synchronous motor.
- Though cheaper than synchronous, induction motor always operates at a lagging power factor.

Ward Leonard Drives

- The synchronous motor can be operated at a leading power factor by overexciting its field.
- Leading reactive power produced by the motor compensates for the lagging reactive power taken by other loads in the plant, thus improving power factor of the plant.
- Overexcitation of the field also enhances maximum torque capability of the motor.
- By employing closed-loop control of its reactive power, synchronous motor can be made to generate leading reactive power equal to lagging reactive power of the plant caused by other loads, making the plant power factor unity.
- The Ward-Leonard drive is used in rolling mills, mine winders, paper mills, elevators, machine tools etc.
- When the load is heavy and intermittent, a slip-ring induction motor is employed and a flywheel is mounted on its shaft.
- This is called the Ward-Leonard-Ilgener scheme (Fig. 2).

Ward Leonard Drives

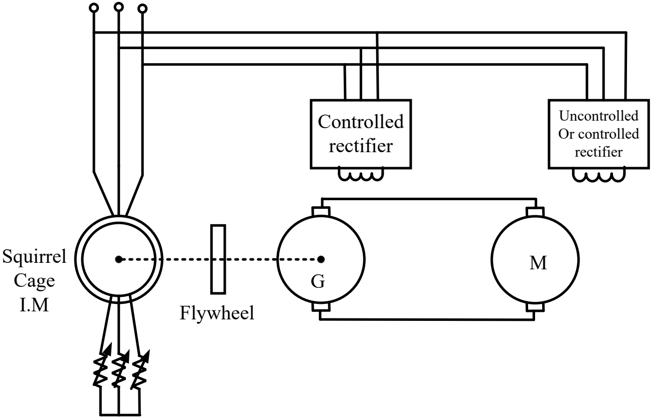

Figure 2. Block-diagram of Ward Leonard-Ilgener drive for intermittent loads.

Ward Leonard Drives

- Rotor resistance control is used to restrict the motor current within permissible limits and to give it a drooping speed-torque characteristic.
- When heavy load demand comes, the flywheel decelerates and gives up some of its stored energy, thus reducing load demand from the supply.
- During light load periods, power is taken from the supply to accelerate the flywheel, which replenishes the energy lost.
- This scheme provides two beneficial effects.
- First, it prevents heavy fluctuations in the supply current and secondly, it permits the use of a relatively smaller size induction motor.
- This scheme finds application in the control of blooming mill drives and colliery winder in steel and mining industries, respectively.
- Because of the large capacity of these drives (few megawatts), the fluctuations in supply current can lead to severe fluctuations of the supply voltage, which adversally affect other loads on the supply.
- Fluctuations can also have an adverse effect on the stability of the source.

Ward Leonard Drives

- It should be noted that when the ac motor is synchronous, supply current fluctuations cannot be reduced by mounting a flywheel on its shaft, because it operates only at a fixed speed.
- Therefore, a slip-ring induction motor is preferred over the synchronous when the load is intermittent and particularly when the drive capacity is large.

Advantages of Ward-Leonard drive:

- It has inherent regenerative braking capability which allows efficient four quadrant operation.
- It can be employed for power factor improvement by using a synchronous motor.
- Because of the inertia of rotating machines, ac supply is dynamically decoupled from the load.
- For example, in paper mill drives, a short duration fluctuation of the supply voltage will not have any affect.
- Further, when it is used to supply important loads such as operation theatres, computers etc., where the continuity of supply is maintained at all costs, the inertia makes enough time available for an uninterruptible power supply to take over in the event of failure of the mains supply.
- In intermittent load applications the Ward-Leonard-Ilgner driver prevents load torque fluctuations to cause source current and voltage fluctuations.

Ward Leonard Drives

Drawbacks of the Ward-Leonard drive:

- High initial cost and low η because of the use of two additional machines of same ratings as that of the main motor.
- Requires more frequent maintenance and produces more noise.
- It has large weight and size, and needs large floor area and foundation.
- Because of these drawbacks, the new installations mainly employ static Ward-Leonard drive.
- Exception is made in the case of high power intermittent load applications → blooming mill drives and mine winders, particularly when the supply system is weak.
- It can also be made for important loads where continuity of supply must be maintained at all costs.

Ward Leonard Drives

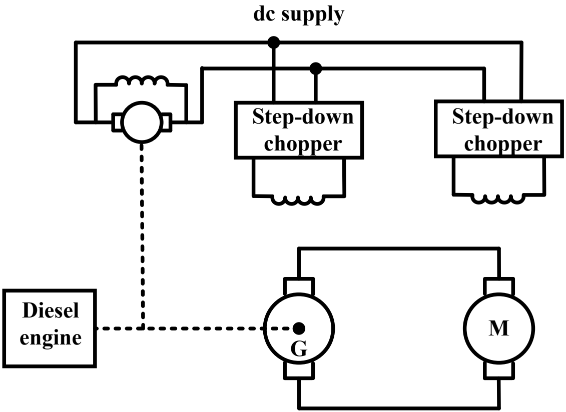

Figure 3. Block-diagram of diesel engine driven Ward Leonard drive.

Ward Leonard Drives

- Another form of Ward-Leonard drive employs a non-electrical prime mover to drive dc generator, e.g. diesel electric locomotive and ship-propulsion, where the generator is driven by a diesel engine or a gas turbine.
- The generator-motor combination works as a torque converter, like a stepless gear, to impart to the motor speed-torque curves required by the load.
- While the motor runs at variable speed, the prime mover, and therefore, the generator runs at a fixed higher speed which may reduce their cost and size and optimize efficiency.
- Regenerative braking is not possible because the prime mover cannot allow the flow of energy in the reverse direction.
- However, dynamic braking can be used. The block diagram of such a drive for diesel-electric locomotive is shown in Fig. 3.
- Here, dc series motor is employed.

Ward Leonard Drives

- Commutator imposes a restriction on the maximum speed of a dc generator.
- This may not allow the prime mover to be driven at an optimum speed. Further, commutator also imposes restriction on the maximum power rating of a dc generator.
- In some large power applications, a number of motors are fed from a common generator.
- The generator should have a size larger than what can be accomplished by a dc generator.
- Furthermore, a dc generator also requires frequent maintenance because of commutator.
- In view of these limitations, a synchronous generator and an uncontrolled rectifier bridge are employed instead of a dc generator.
- Motor voltage is controlled by varying the field of the synchronous generator.

1 Methods of Armature Voltage Control

2 Ward Leonard Drives

3 Transformer and Uncontrolled Rectifier Control

Transformer and Uncontrolled Rectifier Control

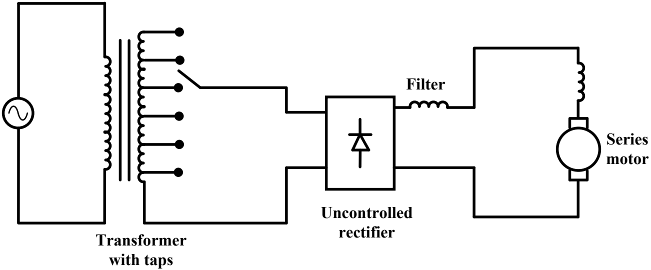

Figure 4. Armature voltage control using a transformer with taps and an uncontrolled rectifier.

- Variable voltage for the dc motor control → either using an auto-transformer or a transformer with tappings (either on primary or on secondary) followed by an uncontrolled rectifier.
- A reactor is connected in the armature circuit → to improve the armature current waveform.

Transformer and Uncontrolled Rectifier Control

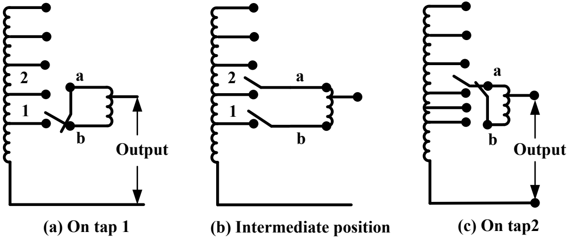

Figure 5. On load tap changer.

- Auto-transformer can be employed only for low power ratings.
- For high power applications a transformer with tappings is employed and tap changing is done with the help of an on load tap changer (Fig. 5) to avoid severe voltage transients, produced due to interruption of current in open circuit transition.
- A mid-point auto-transformer is used to carry out on load tap changing.
- When on tap position 1, both the terminals of auto-transformer are connected together.
- For changing to tap 2, terminal ‘a’ is first connected to tap 2. Terminal ‘b’ is now disconnected from tap 1 and connected to ‘a’.

Transformer and Uncontrolled Rectifier Control

- This scheme is employed in 25 kV single-phase 50 Hz ac traction.
- Features → (a) output voltage can be changed only in steps.
- (b) Rectifier output voltage waveform does not change as the output voltage in reduced.
- A good power factor is maintained at the source and current harmonics introduced in the supply lines do not increase abnormally, like in the case of a controlled rectifier when motor voltage is reduced to a small value.
- (c) Since the use of diode bridge → circuit is not capable of regeneration.

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Thank You

dc Motor Drives

Lecture-12

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Controlled Rectifier Fed dc Drives

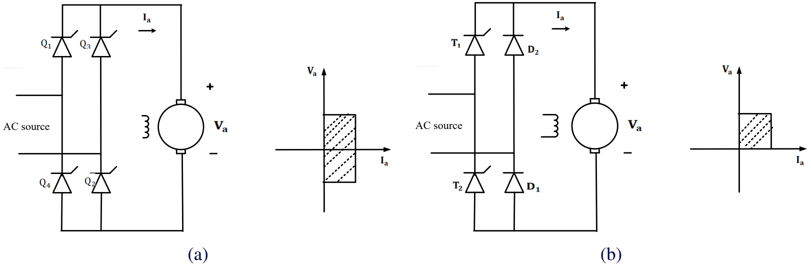


Figure 1. Single-phase controlled rectifier circuits.

- Controlled rectifiers are used to get variable dc voltage from an ac source of fixed voltage.
- Controlled rectifier fed dc drives → Static Ward-Leonard drives.
- As thyristors are capable of conducting current only in one direction, all these rectifiers are capable of providing current only in one direction.

Controlled Rectifier Fed dc Drives

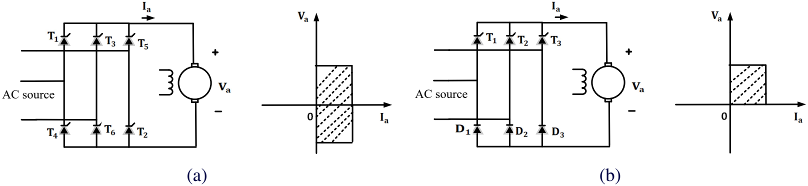


Figure 2. Three-phase controlled rectifier circuits.

- Rectifiers Figs. 1 (a) and 2 (a) provide control of dc voltage in either direction → motor control in quadrant-I and IV → fully-controlled rectifiers.
- Rectifiers Figs. 1 (b) and 2 (b) are called half-controlled rectifiers as they allow dc voltage control only in one direction and motor control in quadrant-I only.
- For low power applications (up to around 10 kW) → single-phase rectifier drives are employed.
- For high power applications → three-phase rectifier drives are used.
- Exception is made in traction where single-phase drives are employed for large power ratings.

1 Controlled Rectifier Fed dc Drives

2 Single-Phase Fully Controlled Rectifier Control of dc Separately Excited Motor

3 Single-Phase Half-Controlled Rectifier Control of dc Separately Excited Motor

Single-Phase Fully Controlled Rectifier Control

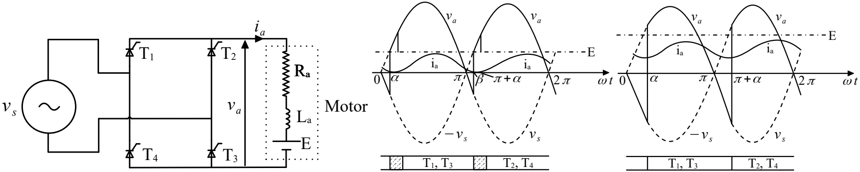


Figure 3. Single-phase fully-controlled rectifier fed dc separately excited motor.

- Motor is shown by its equivalent circuit and field supply is not shown.
- When field control is required, the field is fed from a controlled rectifier or an uncontrolled rectifier. The ac input voltage is defined by

$$v_s = V_m \sin \omega t. \tag{1}$$

- In a cycle of source voltage, thyristors T_1 and T_3 are given gate signals from α to π, and thyristors T_2 and T_4 are given gate signals from $(\pi + \alpha)$ to 2π.

Single-Phase Fully Controlled Rectifier Control

- When I_a does not flow continuously → motor is said to operate in discontinuous conduction.
- When I_a flows continuously → conduction is said to be continuous.
- The drive under consideration, predominantly operates in discontinuous conduction.
- Discontinuous conduction has several modes of operation. The approximate method of analysis is obtained when only the dominant mode of discontinuous conduction is taken into account.
- Motor terminal voltage and current waveforms for the dominant discontinuous conduction and continuous conduction modes are shown in Fig. 3 (b) and (c).
- In discontinuous conduction mode, current starts flowing with the turn-on of thyristors T_1 and T_3 at $\omega t = \alpha$.
- Motor gets connected to the source and its terminal voltage equals v_s.
- The current, which flows against both, E and the source voltage after $\omega t = \pi$, falls to zero at β.

Single-Phase Fully Controlled Rectifier Control

- Due to the absence of current T_1 and T_3 turn-off.
- Motor terminal voltage is now equal to its induced voltage E.
- When thyristors T_2 and T_4 are fired at $(\pi + \alpha)$, next cycle of the motor terminal voltage v_a starts.
- In continuous conduction mode, a positive current flows through the motor, and T_2 and T_4 are in conduction just before α.
- Application of gate pulses turns on forward biased thyristors T_1 and T_3 at α.
- Conduction of T_1 and T_3 reverse biases T_2 and T_4 and turns them off.
- A cycle of v_a is completed when T_2 and T_4 are turned-on at $(\pi + \alpha)$ causing turn-off of T_1 and T_3.
- Since i_a is not perfect dc, the motor torque fluctuates.
- Since torque fluctuates at a frequency of 100 Hz, motor inertia is able to filter out the fluctuations, giving nearly a constant speed and rippleless E.

Discontinuous Conduction

In a cycle of motor terminal voltage v_a, the drive operates in two intervals:

- Duty interval ($\alpha \leq \omega t \leq \beta$) when motor is connected to the source and $v_a = v_s$.
- Zero current interval ($\beta \leq \omega t \leq \pi + \alpha$) when $i_a = 0$ and $v_a = E$.

Drive operation is described by the following equations:

$$v_a = R_a i_a + L_a \frac{d i_a}{dt} + E = V_m sin \, \omega t, \quad \text{for} \quad \alpha \leq \omega t \leq \beta. \tag{2}$$

$$v_a = E \quad \text{and} \quad i_a = o \quad \text{for} \quad \beta \leq \omega t \leq \pi + \alpha. \tag{3}$$

- Solution of Eq. 2 → (i) one due to the ac source ($V_m/Z \, sin \, \omega t - \phi$) and (ii) other due to back-EMF ($-E/R_a$).

$$i_a(\omega t) = \frac{V_m}{Z} sin \, (\omega t - \phi) - \frac{E}{R_a} + K_1 \, e^{-t/\tau_a} \quad \text{for} \quad \alpha \leq \omega t \leq \beta. \tag{4}$$

Where,

$$Z = \sqrt{R_a^2 + (\omega L_a^2)}. \tag{5}$$

$$\phi = tan^{-1}(\omega L_a/R_a) \tag{6}$$

and τ_a is given by E.

Discontinuous Conduction

- Constant K_1 can be evaluated subjecting Eq. 4 to the initial condition $i_a(\alpha) = 0$. Substituting value of K_1 so obtained in Eq. 4 yields

$$i_a(\omega t) = \frac{V_m}{Z}\left[sin\,(\omega t - \phi) - sin\,(\alpha - \phi)\, e^{-(\omega t - \alpha)\, cot\,\phi}\right] - \frac{E}{R_a}\left[1 - e^{-(\omega t - \alpha)\, cot\,\phi}\right], \quad \text{for} \quad \alpha \leq \omega t \leq \beta. \tag{7}$$

- Since $i_a(\beta) = 0$, form Eq. 18

$$\frac{V_m}{Z}\, sin\,(\beta - \phi) - \frac{E}{R_a} + \left[\frac{E}{R_a} - \frac{V_m}{Z}\, sin\,(\alpha - \phi)\right] e^{-(\omega t - \alpha)\, cot\,\phi} = 0. \tag{8}$$

- β can be evaluated by the iterative solution of Eq. 8.
- Since the voltage drop across the armature inductance due to dc component of the armature current is zero.

$$V_a = E + I_a R_a. \tag{9}$$

Where, V_a and I_a dc components of armature voltage and current, respectively.

Discontinuous Conduction

- From Fig. 3 (b),

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t\, d(\omega t) + \int_{\beta}^{\pi+\alpha} E\, d(\omega t)\right] \qquad (10)$$

$$= \frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E}{\pi}. \qquad (11)$$

- Armature current consists of dc component I_a and harmonics. When flux is constant, only the dc component produces steady torque.
- Harmoncs produce alternating torque components, the average value of which is zero.
- Therefore, motor torque is given by

$$\omega_m = \frac{V_m(\cos\alpha - \cos\beta)}{K(\beta - \alpha)} - \frac{\pi R_a}{K^2(\beta - \alpha)} T. \qquad (12)$$

- Boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$.
- Substituing $\beta = \pi + \alpha$ in Eq. 8 gives the critical value of speed ω_{mc} which separates continuous conduction from discontinuous conduction for a given α as

$$\omega_{mc} = \frac{R_a V_m}{Z K I} \sin(\alpha - \phi)\left[\frac{1 + e^{-\pi\cot\phi}}{e^{-\pi\cot\phi} - 1}\right]. \qquad (13)$$

Continuous Conduction

- From Fig. 3 (c),

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t) = \frac{2V_m}{\pi}\cos\alpha. \tag{14}$$

$$\omega_m = \frac{2V_m}{\pi K}\cos\alpha - \frac{R_a}{K^2}T. \tag{15}$$

- Speed torque curves for the drive are shown in Fig. 4.
- The ideal no-load operation is obtained when $I_a = 0$.
- When both thyristor pairs (T_1, T_3) and (T_2, T_4) fail to fire, I_a will be zero.
- This will happen when $E > v_s$ throughout the period for which firing pulses are present.
- $\therefore$, when $\alpha < \pi/2$, E should be greater or equal to V_m and when $\alpha > \pi/2$, E should be greater or equal to $V_m \sin\omega t$.
- $\therefore$ no-load speeds are given by

$$\omega_{m0} = \frac{V_m}{K}, \quad \text{for } o \le \alpha \le \pi/2 \tag{16}$$

$$= \frac{V_m \sin\alpha}{K} \quad \text{for } \pi/2 \le \alpha \le \pi. \tag{17}$$

Continuous Conduction

- Maximum average terminal voltage ($2\,V_m/\pi$) is chosen equally to the rated motor voltage.
- Ideal no-load speed of the motor when fed by a perfect direct voltage of rated value will then be ($2\,V_m/\pi\,K$).
- It is noted that the maximum no-load speed with rectifier control is $\pi/2$ times this value.
- Boundary between continuous and discontinued conduction is shown by the dotted line (Fig. 4).
- For torques less than rated, a low-power drive mainly operates in discontinuous conduction.
- In continuous conduction, the speed-torque characteristics are parallel straight lines, whose slope, according to Eq. 15, depends on the armature resistance R_a.

Continuous Conduction

- The effect of discontinuous conduction is to make speed regulation poor.
- This behaviour shown in Fig. 3 (b) and (c).
- In continuous conduction, for a given α, any increase in torque causes ω_m and E to drop so that I_a and T can increase.
- Average terminal voltage V_a remains constant.
- In discontinuous conduction, any increase in torque and accompanied increase in I_a causes β to increase and V_a to drop.
- Consequently, speed drops by a larger amount.

Continuous Conduction

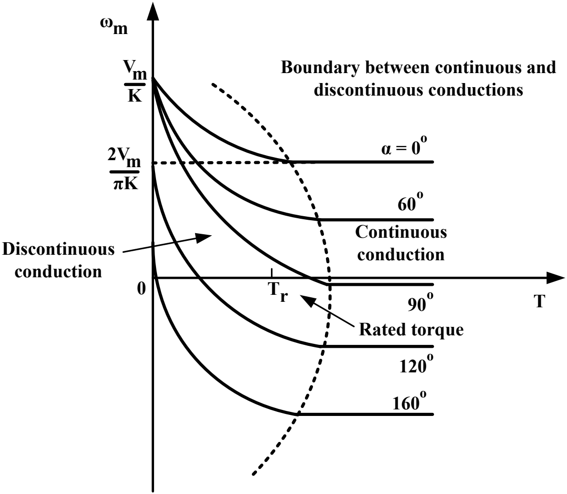


Figure 4. Speed torque characteristics of single-phase fully-controlled rectifier fed dc separately excited motor.

Continuous Conduction

- The drive operates in quadrants I (forward motoring) and IV (reverse regenerative braking).
- These operations can be explained as follows:
- From Eq. 15, under the assumption of continuous conduction, dc output voltage of the rectifier varies with α as shown in Fig. 5 (a).
- When working in quadrant I, ω_m is positive and $\alpha \le 90^\circ$, and polarities of V_a, and E are shown in Fig. 5 (b).
- For positive I_a this causes rectifier to deliver power and the motor to consume it, thus giving forward motoring.
- Polarities of E, I_a, and V_a for quadrant IV operation are shown in Fig. 5 (c).
- E has reversed due to reversal of ω_m.
- Since I_a is still in same direction, machine is working as a generator producing braking torque.
- Further due to $\alpha > 90^\circ$, V_a is negative, suggesting that the rectifier now takes power from dc terminals and transfers it to ac mains.
- This operation of rectifier is called inversion and the rectifier is said to operate as an inverter.

Continuous Conduction

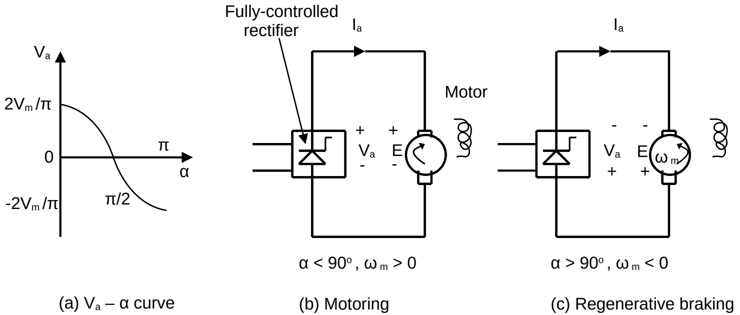


Figure 5. Two-quadrant operation of the drive of single-phase fully-controlled rectifier-fed dc separately excited motor.

- Since generated power is supplied to the source in this operation, it is regenerative braking.
- Two quadrant operation capability of the drive can be utilised only with overhauling loads or other active loads which can drive the motor in reverse direction.
- In a normal two-quadrant operation of a motor one needs forward motoring (quadrant I) and forward braking (quadrant II) which cannot be provided by the drive of Fig. 3 (a).

1 Controlled Rectifier Fed dc Drives

2 Single-Phase Fully Controlled Rectifier Control of dc Separately Excited Motor

3 Single-Phase Half-Controlled Rectifier Control of dc Separately Excited Motor

Single-Phase Half-Controlled Rectifier Control of dc Separately Excited Motor

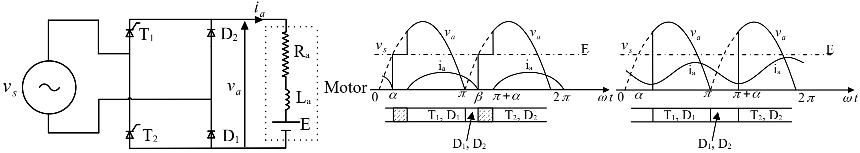


Figure 6. Single-phase half-controlled-rectifier fed separately excited motor.

- In a cycle of source voltage, T_a receives gate pulse from α to π and T_2 from $(\pi + \alpha)$ to 2π.
- In discontinuous conduction mode, when T_1 is fired at α, motor gets connected to the source through T_1 and D_1 and $v_a = v_s$.
- The armature current flows and D_2 gets forward biased at π.
- Consequently, armature current freewheels through the path formed by D_1 and D_2, and the motor terminal voltage is zero.
- Conduction of D_2 reverse biases T_1 and turns it off.
- Armature current drops to 0 at β and stays zero until T_2 is fired at $(\pi + \alpha)$.

Discontinuous Conduction

A cycle of motor terminal voltage consists of three intervals (Fig. 6 (b)):

- (i) Duty internal ($\alpha \le \omega t \le \pi$): Armature current is given as

$$i_a(\pi) = \frac{V_m}{Z}\left[sin\,(\pi - \phi) - sin\,(\alpha - \phi)\,e^{-(\pi - \alpha)\,cot\,\phi}\right] - \frac{E}{R_a}\left[1 - e^{-(\pi - \alpha)\,cot\,\phi}\right]. \quad (18)$$

- (ii) Freewheeling interval ($\pi \le \omega t \le \beta$): Operation is governed by the following equation:

$$i_a R_a + L_a \frac{di_a}{dt} + E = 0. \quad (19)$$

- Solution of Eq. 19 subject to $i_a(\pi)$ as the initial current yields

$$i_a(\omega t) = \frac{V_m}{Z}\left[sin\,\phi\,e^{-(\omega t - \pi)}cot\,\phi - sin\,(\alpha - \phi)\,e^{-(\omega t - \alpha)cot\,\phi}\right] -0\,\frac{E}{R_a}[1 - e^{-(\omega t - \alpha)cot\,\phi}], \quad \text{for} \quad \pi \le \omega t \le \beta. \quad (20)$$

- (iii) Zero current interval ($\beta \le \omega t \le \pi + \alpha$):

$$e^{\beta\,cot\,\phi} = \frac{R_a V_m}{Z E}\left[sin\,\phi\,e^{\pi\,cot\,\phi} - sin\,(\alpha - \phi)\right] \quad (21)$$

Discontinuous Conduction

- (iii) Zero current interval ($\beta \leq \omega t \leq \pi + \alpha$):

$$e^{\beta \cot \phi} = \frac{R_a V_m}{Z E} \left[\sin \phi \, e^{\pi \cot \phi} - \sin(\alpha - \phi) e^{\alpha \cot \phi} \right] + e^{\alpha \cot \phi}. \tag{22}$$

- β can be calculated by the solution of Eq. 22. Now,

$$V_a = \frac{1}{\pi} \left[\int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t) + \int_{\beta}^{\pi + \alpha} E \, d(\omega t) \right] \tag{23}$$

$$= \frac{V_m (1 + \cos \alpha) + (\pi + \alpha - \beta) E}{\pi}. \tag{24}$$

$$\omega_m = \frac{V_m (1 + \cos \alpha)}{K (\beta - \alpha)} - \frac{\pi R_a}{K^2 (\beta - \alpha)} T. \tag{25}$$

- Boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$.
- Substituting $\beta = \pi + \alpha$ in Eq, 22 gives the critical speed ω_{mc}, which separates continuous conduction from discontinuous conduction for a given α.

$$\omega_{mc} = \frac{R_a}{K} \frac{V_m}{Z} \left[\frac{\sin \phi \, e^{-\alpha \cot \phi} - \sin(\alpha - \phi) \, e^{-\pi \cot \phi}}{1 - e^{-\pi \cot \phi}} \right]. \tag{26}$$

Continuous Conduction

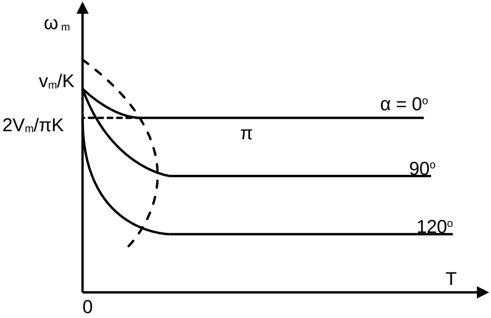


Figure 7. Speed torque curves of single-phase half-controlled rectifier fed separately excited motor.

- From Fig. 6 (c),

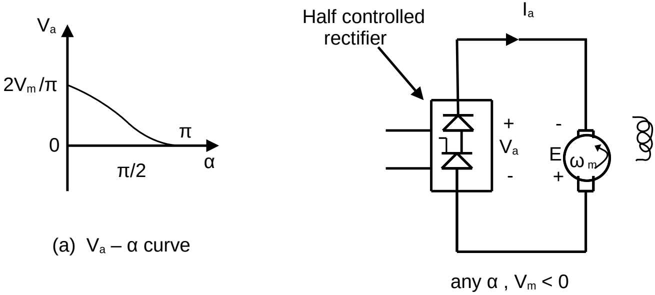
$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t) = \frac{V_m}{\pi}(1 + \cos\alpha). \tag{27}$$

$$\omega_m = \frac{V_m}{\pi K}(1 + \cos\alpha) - \frac{R_a}{K^2}T. \tag{28}$$

Continuous Conduction

- Operation of drive, which operates in quadrant I only, is represented by the equivalent circuit of Fig. 5 (b).
- It is useful to note why the drive should not be operated in quadrant IV.
- Fig. 8 (a) shows plot of V_a with α (Eq. 27) for half-controlled rectifier for continuous conduction operation.
- The output voltage cannot be reversed.
- When coupled to an active load, the motor speed can reverse, reversing E as shown in Fig. 8 (b).
- As current direction does not change, machine now works as a generator producing braking torque.
- Since, rectifier voltage cannot reverse, generated energy cannot be transferred to ac source, and therefore, it is absorbed in the armature circuit resistance.
- Braking so obtained is nothing but the reverse voltage braking (plugging).
- Such a braking is not only inefficient but also causes a large current $I_a = (V_a + E)/R_a$ to flow through the rectifier and motor.

Continuous Conduction



(a) V_a – α curve

(b) Braking operation

Figure 8. Reverse voltage braking operation of the drive of Fig. 6 (a).

- Since it cannot be regulated by adjustment of firing angle, it will damage the rectifier and motor.
- $\therefore$ when load is active, care should be taken to avoid such a operation. If such a operation cannot be avoided, fully-controlled rectifier should be used.
- A half-controlled single-phase rectifier is cheaper and gives higher power factor compared to single-phase fully-controlled rectifier.
- But then it only provides control in quadrant I.

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Thank You

dc Motor Drives

Lecture-13

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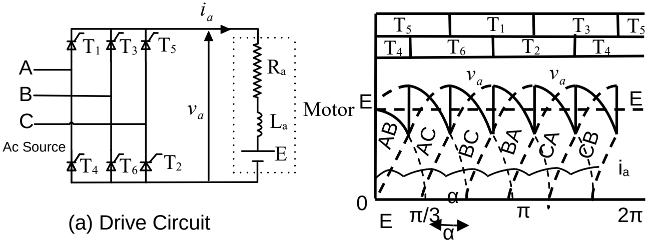
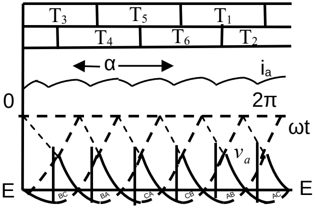
1 Three-Phase Fully-Controlled Rectifier Control of dc Separately Excited Motor

Three-Phase Fully-Controlled Rectifier Control



(a) Drive Circuit

(b) Motoring operation, α = 30^0



(c) Motoring operation, α = 140^0

Figure 1. Three-phase fully-controlled converter control of separately excited motor.

Three-Phase Fully-Controlled Rectifier Control

- Thyristors are fired in the sequence of their numbers with a phase difference of 60° by gate pulses of 120° duration.
- Each thyristor conducts for 120°, and two thyristors conduct at a time, one from upper group (odd numbered thyristors) and the other from lower group (even numbered thyristors) applying respective line voltage to the motor.
- Transfer of current from an outgoing to incoming thyristor → when the respective line voltage is of such a polarity that not only forward biases the incoming thyristor, but also leads to the reverse biasing of the outgoing when incoming turns-on.
- Thus, firing angle for a thyristor is measured from the instant when the respective line voltage is zero and increasing.
- For example, the transfer of current from thyristor T_5 to thyristor T_1 can occur as long as the line voltage v_{AC} is positive.
- Hence, for thyristor T_1 firing angle α is measured from the instant $v_{AC} = 0$ and increases as shown in Fig. 1 (b) and (c).

Three-Phase Fully-Controlled Rectifier Control

- If line voltage v_{AB} is taken as the reference voltage, then

$$v_{AB} = V_m \sin \omega t, \quad \text{and} \tag{1}$$

$$\alpha = \omega t - \pi/3. \tag{2}$$

  Where, V_m is the peak of line voltage.
- Motor terminal voltage and current waveforms for continuous conduction are shown in Fig. 1 (b) and (c) for motoring and braking operations, respectively.
- The discontinuous conduction is neglected here because it occurs in a narrow region of its operation.
- For the motor terminal voltage cycle from $\alpha + \pi/3$ to $\alpha + 2pi/3$ (from Fig. 1 (b) and (c)).

$$V_a = \frac{3}{\pi} \int_{\alpha+\pi/3}^{\alpha+2\pi/3} V_m \sin \omega t \, d(\omega t) \tag{3}$$

$$= \frac{3}{\pi} V_m \cos \alpha. \tag{4}$$

$$\omega_m = \frac{3 V_m}{\pi K} \cos \alpha - \frac{R_a}{K^2} T. \tag{5}$$

- When discontinuous conduction is ignored, speed-torque curves of Fig. 2 are obtained.
- Consequently, drive operates in quadrants I and IV.

Three-Phase Half-Controlled Rectifier Control of dc Separately Excited Motor

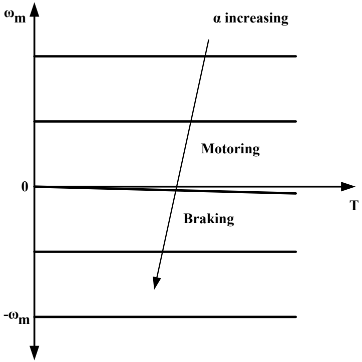


Figure 2. Speed torque curves of drive of Fig. 1 (a) neglecting discontinuous conduction.

- For rectifier circuit, under continuous conduction

$$V_a = \frac{3\,V_m}{2\,\pi}\,(1 + cos\,\alpha). \tag{6}$$

$$\omega_m = \frac{3\,V_m}{2\,\pi\,K}\,(1 + cos\,\alpha) - \frac{R_a}{K^2}\,T. \tag{7}$$

- Consequently, the drive operates only in quadrant I.

Multiquadrant Operation of dc Separately Excited Motor fed from Fully-Controlled Rectifier

- Here, the multi-quadrant operation with regenerative braking is considered.
- In these drives, current control is always provided in order to limit current within a safe limit during transient operations.
- When closed-loop speed control is provided, the current is limited using inner current control loop. Otherwise, the drive is operated with current limit control.
- Three schemes are used
  (a) Single fully-controlled rectifier with a reversing switch.
  (b) Dual converter.
  (c) Single fully controlled rectifier in the armature with field current reversal.
- All these schemes are capable of providing four-quadrant operation.
- They are also employed when two-quadrant operation consisting of forward motoring and forward regenerative braking is required.
- It may be noted that a fully controlled converter is capable of providing forward motoring (quadrant I) and reverse regenerative braking (quadrant IV) operations.

Single Fully-Controlled Rectifier with a Reversing Switch

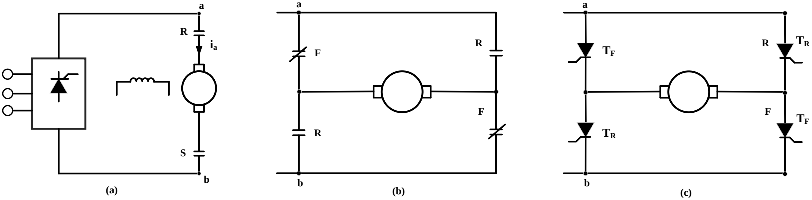


Figure 3. Four quadrant drive employing single converter and a reversing switch.

- A fully-controlled rectifier feeds the motor through a reversing switch RS which is used to reverse the armature connection with respect to the rectifier.
- A fully- controlled rectifier is capable of providing operation in quadrants I and IV.
- The reversal of the armature connection provides operation in quadrant III and II.
- The reversing switch may consist of a relay-operated contactor with two normally open and two normally closed contacts as shown in Fig. 3 (b).

Single Fully-Controlled Rectifier with a Reversing Switch

- When slow operation and frequent maintenance associated with the contactor is not acceptable, reversing switch is realized using four thyristors as shown in Fig. 3 (c).
- With thyristor pair T_F on (and pair T_R off) operation is obtained in quadrants I and IV and with pair T_R on (and T_F off) the operation is provided in quadrants III and II.
- In both the configurations of RS, the switching is done at zero current in order to avoid voltage spikes and to reduce its rating.
- The firing angle of the rectifier is set at the highest value.
- It works as an inverter and reduces armature current to zero.
- After the zero current is sensed, firing pulses are stopped.

Single Fully-Controlled Rectifier with a Reversing Switch

The speed reversal (transfer of operation from quadrant I to III or from quadrant III to I) is done as follows:

- A delay time of 2 to 10 ms is provided to make sure that the thyristors which were conducting have all fully turned off.
- Such long delay (compared to thyristor turn-off time which is of few hundred micro- seconds) is required in order to take care of errors in zero current sensing.
- Now the armature connection is reversed and firing pulses are released with the firing angle set at the highest value.
- The current control adjust the firing angle continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates the motor (again at the maximum allowable current) to the desired speed in the reverse direction.
- The operation at the maximum current during speed reversal ensures braking and acceleration at the maximum motor torque, ensuring fast reversal.

Dual Converter

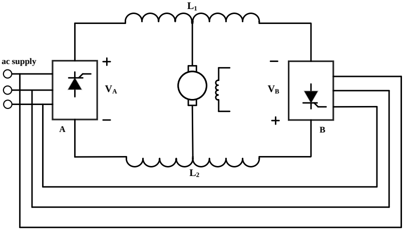


Figure 4. Dual converter control of dc separately excited motor. A and B are fully controlled rectifiers. Inductors L_1 and L_2 are used only with simultaneous control.

- A dual-converter (Fig. 4) consists of two fully-controlled rectifiers connected in anti-parallel across the armature.
- For power ratings upto around 10 kW, sigle-phase fully-controlled rectifiers can be used.
- For higher ratings, three-phase fully controlled rectifiers are employed.
- Rectifier A, which provides positive motor current and voltage in either direction, allows motor control in quadrants I and IV.
- Rectifier B provides motor control in quadrants III and II, because it gives negative motor current and voltage in either direction.

Dual Converter

There are two methods of control for the dual converter:

- (a) In simultaneous control both the rectifiers are controlled together.
- In order to avoid dc circulating current between rectifiers, they are operated to produce same dc voltage across the motor terminals.
- Thus $V_A + V_B = 0$.

$$\cos\alpha_A + \cos\alpha_B = 0 \text{ or } \alpha_A + \alpha_B = 180^\circ. \tag{8}$$

- Although, control of firing angle according to Eq. 8 prevents dc circulating current, ac current does circulate due to the difference between instantaneous output voltages of the two rectifiers.
- Inductors L_1 and L_2 are added to reduce ac circulating current.
- Because of the flow of ac circulating current, simultaneous control is also known as circulating current control.
- In a three-phase dual converter, inductors are chosen to allow a circulating current of 30 % of full load current.
- This completely eliminates discontinuous conduction, and therefore, gives good speed regulation in the complete range of the drive.

Dual Converter

The speed reversal is done as follows:

- When operating in quadrant I, rectifier A will be rectifying ($0 < \alpha_A < 90^\circ$) and rectifier B will be inverting ($90^\circ < \alpha_B < 180^\circ$).
- For speed reversal α_A is increased and α_B is decreased to satisfy Eq. 8.
- The motor back-EMF exceeds magnitudes of V_A and V_B.
- The armature current shifts to rectifier B and the motor operate in quadrant II.
- The current control loop adjusts the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the reverse direction.
- As α_B is changed, α_A is also changed to satisfy Eq. 8.
- The inductances L_1 and L_2 increase the weight, volume, cost and reversal time.
- The circulating current increases the losses.
- Sudden drop in source voltage can cause large current to flow through the rectifier working as inverter, blowing its thyristors.

Dual Converter

- (b) In non-simultaneous or non-circulating current control method, one rectifier is controlled at a time.
- Consequently, no circulating current flows and inductors L_1 and L_2 are not required.
- This eliminates losses associated with circulating current and weight and volume associated with inductors.
- But then discontinuous conduction occurs at light loads and control is rather complex.

The speed reversal is carried out as follows:

- When operating in quadrant I → rectifier A will be supplying the motor and rectifier B will not be operating.
- The firing angle of rectifier A is set at the highest value.
- The rectifier works as an inverter and forces the armature current to zero.

Dual Converter

- After zero current is sensed, a dead time of 2 to 10 ms is provided to ensure the turn-off of all thyristors of rectifier A.
- Now, firing pulses are withdrawn from rectifier A and transferred to rectifier B.
- The firing angle α_B is set initially at the highest value.
- Now onwards the current control loop adjust the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the reverse direction.
- The dead time, and therefore, the reversal time can be reduced by employing methods which can sense the current zero accurately.
- When this is done, non-simultaneous control provides faster response than simultaneous control.
- Hence, non-simultaneous control is widely used.

Field Current Reversal

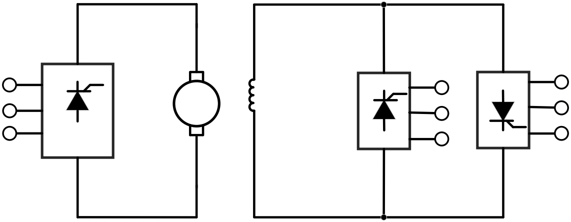


Figure 5. Four quadrant drive with field reversal.

- As shown in Fig. 5, armature is fed from a fully-controlled rectifier and the field from a dual converter so that field current can be reversed.
- With field current in one direction, the motor operates in quadrants I and IV.
- When field current is reverted, it operates in quadrants III and II.
- The dual converter operates with non-simultaneous control.

Field Current Reversal

The speed reversal is done as follows:

- The armature rectifier firing angle is set at the highest value to force the armature current to zero and then firing pulses are withdrawn.
- The firing angle of the rectifier supplying the field is now set at the highest value.
- It operates as an inverter and the field current is forced to zero.
- After a suitable dead time, the second rectifier is activated at the lowest firing angle.
- When the field current has nearly settled and the motor back-EMF has reversed, the firing pulses of the armature rectifier are released so as to set the firing angle at the highest value.
- Now onwards the current control loop adjust the firing angle continuously to brake and then accelerate the motor at a constant current to the desired speed in the reverse direction.
- When speed control in wide range is required, field current is also controlled.
- In armature voltage control schemes of Figs. 3 and 4, the field is then supplied by either a fully- controlled or a half-controlled rectifier.
- In the scheme of Fig. 5, dual converter is utilized for the control of field current.

Comparison of Conventional and Static Ward Leonard Schemes

The conventional Ward Leonard scheme suffers from the following disadvantages compared to Static Ward Leonard scheme:

- (i) higher initial cost due to use of two additional machines of same rating as the main motor
- (ii) larger weight and size
- (iii) needs more floor space and proper foundation
- (iv) requires more frequent maintenance
- (v) higher noise
- (vi) lower efficiency due to higher losses.

Comparison of Conventional and Static Ward Leonard Schemes

The static Ward Leonard scheme, in comparison with conventional, has following disadvantages:

- (i) There is no provision for load equalisation. Therefore, when used in intermittent load applications, load fluctuations cause heavy fluctuations of supply current and voltage, which adversely effects quality of supply and stability of generating plant.
- (ii) It generates considerable amount of harmonics, which again adversally affect quality of supply and performance of generating plant.
- (iii) Operates at a low power factor particularly at low speeds. For large power drives with low line capacity, low power factor and large harmonics cause great concern.

On the whole, static Ward Leonard drive is preferred over conventional Ward Leonard drive in most applications.

- The conventional drive is however preferred for large-size intermittent load applications where drive capacity forms a significant part of source capacity.
- It is noted that when the source of power is non-electrical, as in diesel electric locomotive or ship propulsion, conventional Ward Leonard drive can only be used.

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Thank You

dc Motor Drives

Lecture-14

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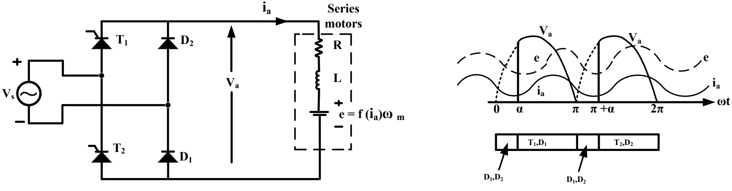
Rectifier Control of dc Series Motor



(a) (b)

Figure 1. Single-phase half-controlled rectifier fed series motor.

- Single-phase controlled rectifier fed dc series motors are employed in traction.
- A single-phase half-controlled rectifier-fed dc series motor is shown in Fig. 1 (a).
- Since back-EMF decreases with armature current, discontinuous conduction occurs only in a narrow range of operation. Hence, it will be neglected here.
- The waveforms of v_a, i_a and instantaneous back-EMF e for continuous conduction are shown in Fig. 1 (b).
- Although, in steady state, fluctuations in speed are negligible, e is not constant but fluctuates with i_a.
- For a given speed, e is related to i_a through the magnetization curve of motor, which is nonlinear owing to saturation. Thus

$$e = f(i_a)\,\omega_m. \tag{1}$$

Rectifier Control of dc Series Motor

- Motor operation is described by following equations for duty and freewheeling intervals, respectively.

$$V_m \sin \omega t = R_a i_a + L_a \frac{d i_a}{dt} + f(i_a)\, \omega_m, \quad \text{for} \quad \alpha \le \omega t \le \pi. \tag{2}$$

$$0 = R_a i_a + L_a \frac{d i_a}{dt} + f(i_a)\, \omega_m, \quad \text{for} \quad \pi \le \omega t \le (\pi + \alpha). \tag{3}$$

- Since the presence of terms $f(i_a)$, Eqs. 2 and 3 are nonlinear differential equations and can only be solved numerically.
- A simple method of analysis is obtained when e is replaced by its average value E_a such that

$$E_a = K_a \omega_m. \tag{4}$$

Where, $K_a = f(I_a)$.

- Since the drop across the inductance L_a due to dc component of I_a is zero.

$$V_a = E_a + I_a R_a \tag{5}$$

$$\omega_m = \frac{V_a - I_a R_a}{K_a} \quad \text{and} \tag{6}$$

$$T = K_a i_a. \tag{7}$$

Rectifier Control of dc Series Motor

- For continuous conduction, V_a for half-controlled and fully-controlled single-phase rectifiers is given as

$$V_a = \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{V_m}{\pi} (1 + \cos \alpha). \tag{8}$$

$$V_a = \frac{1}{\pi} \int_{\alpha}^{\pi + \alpha} V_m \sin \omega t \, d(\omega t) = \frac{2 V_m}{\pi} \cos \alpha. \tag{9}$$

- Following sequence of steps are used to calculate speed-torque characteristic for a given α taking into account non-linearly of the magnetic circuit: A value is chosen for I_a.
- Corresponding value of K_a is obtained from the magnetization characteristic of the motor.
- For the known value of α, calculate V_a from Eqs. 8 or 9, depending on the rectifier circuit used.
- Now ω_m and T are obtained from Eqs. 6 and 7, respectively.
- Nature of speed-torque characteristics for the drive of Fig. 1 (a) is shown in Fig. 2.

Rectifier Control of dc Series Motor

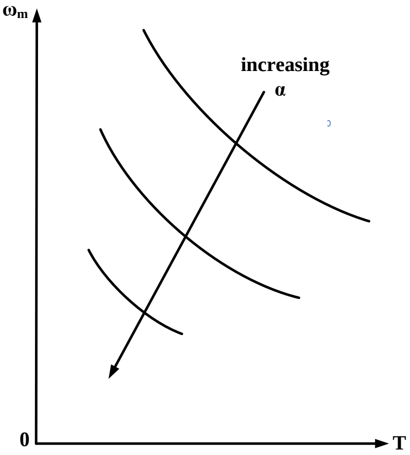


Figure 2. Speed-torque curves of series motor fed from a controlled rectifier.

1. Rectifier Control of dc Series Motor
2. Control of Fractional hp Motors
3. Chopper-Controlled dc Drives

Control of Fractional hp Motors

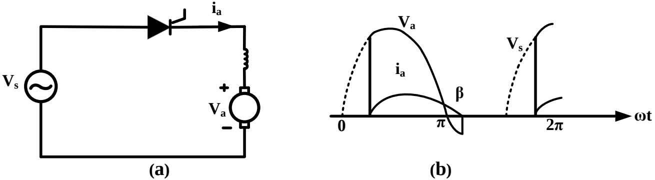


Figure 3. Control of universal motor by a single thyristor.

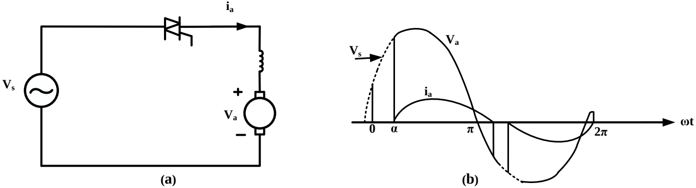


Figure 4. Control of universal motor by an ac voltage controller.

Control of Fractional hp Motors

- Because of low-cost single-phase half-wave controlled rectifier of Fig. 3 (a), employing a single thyristor, is commonly used for the control of fractional hp universal, dc series and permanent magnet de motors.
- Such drives are employed in hand tools and small domestic appliances.
- Motor terminal voltage and armature current waveforms for universal motor are shown in Fig 3 (b).
- The drive operates is discontinuous conduction with a large zero current interval and large current ripple.
- Consequently, efficiency is poor, speed regulation is large and speed may fluctuate around its average value when the inertia is low.
- Sometimes a freewheeling diode is added to reduce the duration of zero current interval.
- Universal motors may also be controlled by a triac ac voltage controller as shown in Fig. 4 (a).
- The triac is fired at α and $(\pi + \alpha)$.
- Now the machine armature carries ac current (Fig. 4 (b)).
- Because of reduced duration of zero current interval, the drive has negligible speed fluctuations and lower speed regulation.

Supply Harmonics, Power Factor and Ripple in Motor Current

Rectifier-fed de drives have the following drawbacks:

- (i) Distortion of supply: Source current of a rectifier has harmonics.
- In a weak ac source, with high internal impedance, current harmonies distort source voltage.
- Furthermore, temporary short circuit of lines during commutation of thyristors, causes sharp current pulses, which further distort source voltage.
- Source voltage and current distortions have several undesirable effects including interference with other loads connected to the source and radio frequency interference in communication equipment.
- (ii) Low power factor: Assuming sinusoidal supply voltage, power factor (PF) of a rectifier can be defined as

$$\text{PF} = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{V I_1 \, cos\, \phi_1}{V I_{rms}}. \tag{10}$$

Where, V and I_{rms} are rms source voltage and current, respectively.

Supply Harmonics, Power Factor and Ripple in Motor Current

- I_1 and ϕ_1 are fundamental component of source current and phase difference between V and I_1, respectively.

$$\text{PF} = \frac{I_1}{I_{rms}} \cos\phi_1 = \mu \cos\phi_1. \tag{11}$$

Where, μ is called distortion factor and $\cos\phi_1$ is the displacemnet factor.

- The distortion in source current makes μ lower than 1.
- When motor current is assumed to be perfect dc, ϕ_1 has a value of α for fully controlled single phase and three phase rectifiers and $\alpha/2$ for single phase half controlled rectifiers, thus giving displacement factors of $\cos\alpha$ and $\cos\alpha/2$, respectively.
- ∴ supply power factor is low when the drive operates at low speeds.
- Pulsewidth modulated rectifiers are being built using insulated gate bipolar transistors (IGBT) and gate turn-off thyristors (GTO) as they have high power factor and low harmonic content in source current but then their η is low because of high switching losses.

Supply Harmonics, Power Factor and Ripple in Motor Current

- (iii) Ripple in motor current: The rectifier output voltage is not perfect dc but consists of harmonics in addition to de component.
- ∴ motor current also has harmonics in addition to dc component.
- The presence of harmonics, makes rms and peak values of motor currents higher than average value (dc component).
- Since flux is constant, torque is contributed only by the average value of current.
- The harmonics produce fluctuating torques, the average value of which is zero.
- The presence of harmonics increases both copper loss and core loss.
- Hence for an allowable temperature rise, the torque and power outputs have lesser values than rated values.
- Due to the presence of harmonics, peak value of current increases and commutation condition deteriorates.
- Hence, the current that the motor can commutate without sparking at the brushes has a lower dc component than the rated motor current.
- Thus, the derating of motor occurs due to this also.
- On the whole, the motor output (power and torque) must be restricted considerably below rated value to avoid thermal overloading and sparking at brushes.

1 Rectifier Control of dc Series Motor

2 Control of Fractional hp Motors

3 Chopper-Controlled dc Drives

Chopper-Controlled dc Drives

- Choppers, also commonly known as dc-to-dc converters, are used to get variable dc voltage from a dc source of fixed voltage.
- Self-commutated devices, such as MOSFETS, power transistors.
- IGBT (insulated gate bipolar transistor), GTO (gate turn-off thyristor) and IGCT (insulated gate commutated thyristor), are preferred over thyristors for building choppers because they can be commutated by a low power control signal and do not reed commutation circuit.
- Further, they an be operated at a higher frequency for the same rating.
- The operation at a high frequency improves motor performance by reducing current ripple and eliminating discontinuous conduction.
- While MOSFETS are used for low power and low voltage applications, IGBT and power transistor are employed in medium power ratings, and GTO and IGCT are employed for high power ratings.
- One important feature of chopper control is that regenerative braking can be carried out up very low speeds even when the drive is fed from a fixed voltage dc source.

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Thank You

dc Motor Drives

Lecture-15

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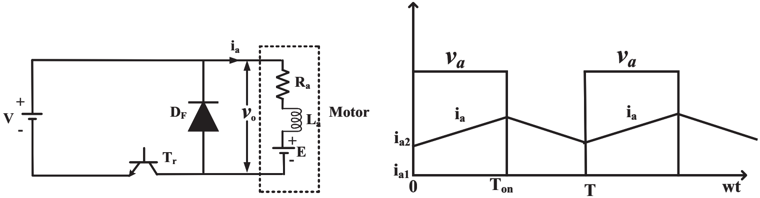
1 Chopper Control of Separately Excited dc Motors

2 Chopper Control of Series Motor

Chopper Control of Separately Excited dc Motors



(a) (b)

Figure 1. Chopper control of separately excited motor.

Motoring Control

- A transistor chopper controlled separately excited motor drive is shown in Fig. 1 (a).
- Transistor T_r is operated periodically with period T and remains on for a duration t_{on}.

Chopper Control of Separately Excited dc Motors

- The chopper operates at a high enough frequency to ensure continuous conduction.
- Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 1 (b).
- During on-period of the transistor, $o \leq t \leq t_{on}$, the motor terminal voltage is V.
- The operation is described by

$$R_a i_a + L_a \frac{d\,i_a}{dt} + E = V, \quad o \leq t \leq t_{on}. \tag{1}$$

- In this interval, armature current increases from i_{a1} to i_{a2}. Since the motor is connected to the source during this interval, it is called duty interval.
- At $t = t_{on}$, T_r is turned-off.
- Motor current freewheels through diode D_F and motor terminal voltage is zero during interval $t_{on} \leq t \leq T$.

Chopper Control of Separately Excited dc Motors

- Motor operation during this interval, known as the freewheeling interval, is described by

$$R_a i_a + L_a \frac{d\,i_a}{dt} + E = 0, \quad t_{on} \le t \le T. \tag{2}$$

- Motor current decreases from i_{a2} to i_{a1} during this interval.
- Ratio of duty interval t_{on} to chopper period T is called duty ratio or duty cycle, δ. Thus

$$\delta = \frac{\text{Duty interval}}{T} = \frac{t_{on}}{T}. \tag{3}$$

- From Fig. 1 (b),

$$V_a = \frac{1}{T} \int_0^{t_{on}} V\,dt = \delta\,V. \tag{4}$$

- Now,

$$I_a = \frac{\delta\,V - E}{R_a} \quad \text{and} \tag{5}$$

$$\omega_m = \frac{\delta\,V}{K} - \frac{R_a}{K^2}\,T. \tag{6}$$

Regenerative Braking

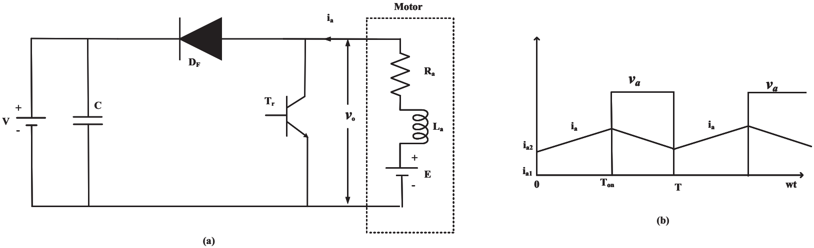


Figure 2. Regenerative braking of the separately excited motor by chopper control.

- Chopper for regenerative braking operation is shown in Fig. 2 (a).
- Transistor T_r is operated periodically with a period T and on-period of t_{on}.
- Waveforms of motor terminal voltage V_a and armature current i_a for continuous conduction are shown in Fig. 2 (b).
- Usually an external inductance is added to increase the value of L_a When T_r is on, i_a increase from i_{a1} to i_{a2}.
- The mechanical energy converted into electrical by the motor, now working as a generator, partly increases the stored magnetic energy in armature circuit inductance and remainder is dissipated in armature resistance and transistor.

Regenerative Braking

- When T_r is turned off, armature current flows through diode D and source V, and reduces from i_{a2} to i_{a1}.
- The stored electromagnetic energy and energy supplied by machine is fed to the source.
- The interval $0 \leq t \leq t_{on}$ is now called energy storage interval and interval $t_{on} \leq t \leq T$ the duty interval.
- If δ is defined as the ratio of duty interval to period T, then

$$\delta = \frac{\text{Duty interval}}{T} = \frac{T - t_{on}}{T}. \tag{7}$$

- From Fig. 2 (b),

$$V_a = \frac{1}{T} \int_{t_{on}}^{T} V \, dt = \delta V. \tag{8}$$

- Now,

$$I_a = \frac{E - \delta V}{R_a} \tag{9}$$

- Since I_a has reversed

$$T = -K I_a. \tag{10}$$

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2} T. \tag{11}$$

Regenerative Braking

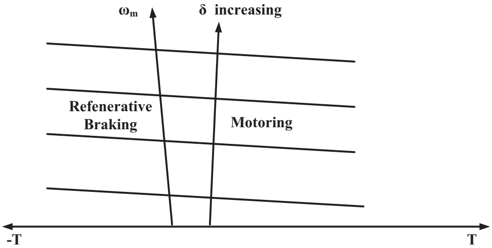


Figure 3. Speed torque curves of chopper controlled separately excited motor.

Motoring and Regenerative Braking

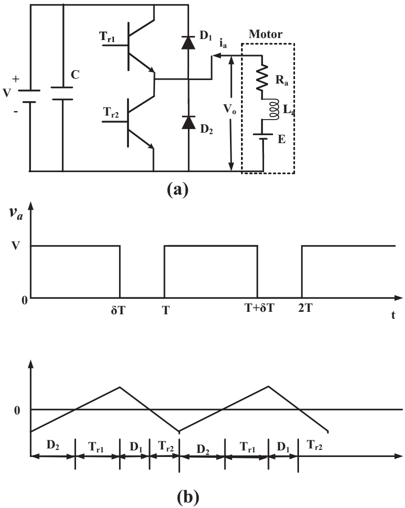


Figure 4. Chopper for forward motoring and braking control.

Motoring and Regenerative Braking

- Chopper circuits of Figs. 1 and 2 can be combined to get a two-quadrant chopper of Fig. 4, which can provide motoring and regenerative braking operations in the forward direction.
- Transistor T_{r1} with diode D_1 form a chopper circuit similar to that of Fig. 1, and therefore, provide control for forward motoring operation.
- Transistor T_{r2} with diode D_2 form a chopper circuit similar to that of Fig. 2, and therefore, provide control for forward separately excited motor regenerative braking operation.
- Thus, for motoring operation transistor T_{r1} is controlled and for braking operation transistor T_{r2} is controlled.
- Shifting of control from T_{r1} to T_{r2} shifts operation from motoring to braking and vice versa.
- In servo drives where fast transition from motoring to braking and vice versa is required, both T_{r1} and T_{r2} are controlled simultaneously.
- In a period T, T_{r1} is given gate drive from 0 to δT and T_{r2} is given gate drive from δT to T, where δ is the duty ratio for T_{r1}.

Motoring and Regenerative Braking

- $\therefore$ from 0 to δT motor is connected to source either through T_{r1} or D_2 depending on whether the motor current i_a is positive or negative.
- Since $V > E$, during this period the rate of change of current is always positive.
- Similarly from δT to T, motor armature is shorted either through D_1 or T_{r2} depending on whether i_a is positive or negative and during this period rate of change of current is always negative.
- Motor terminal voltage and current waveforms are shown in Fig. 4 (b).
- From Fig. 4 (b)

$$V_a = \delta V \quad \text{and} \tag{12}$$

$$I_a = \frac{\delta V - E}{R_a}. \tag{13}$$

- The Eq. 13 suggests that motoring operation (+ve I_a) takes place when $\delta > (E/V)$ and regenerative braking operation takes place when $\delta < (E/V)$ and transition from to braking and vice versa occurs when $\delta = (E/V)$.
- The above equations are similar to those obtained for chopper of Fig. 1, and therefore, given the same numbers.

Dynamic Braking

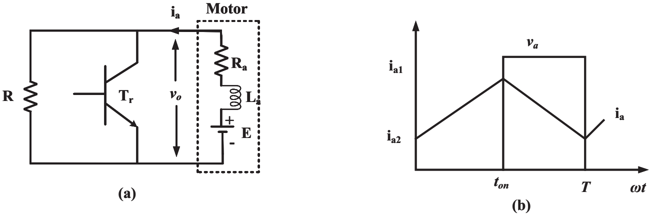


Figure 5. Dynamic braking of the separately excited motor by chopper control.

- Dynamic braking circuit and its waveforms are shown in Fig. 5.
- During the interval $0 \le t \le t_{on}$, i_a increases from i_{a1} to i_{a2}.
- A part of generated energy is stored in inductance and rest is dissipated in R_a and T_r.
- During interval $t_{on} \le t \le T$ i_a decreases from i_{a2} to i_{a1}.

Dynamic Braking

- The energies generated and stored in inductance are dissipated in braking resistance R_B, R_a and diode D.
- Transistor T_r controls the magnitude of energy dissipated in R_B, and therefore, controls its effective value.
- If i_a is assumed to be rippleless dc, then energy consumed E_N by R_B during a cycle of chopper operation is

$$E_N = I_a^2 R_B (T - t_{on}). \tag{14}$$

- Average power consumed by R_B

$$P = \frac{E_N}{T} = I_a^2 R_B (1 - \delta). \tag{15}$$

- Effective value of R_B

$$R_{BE} = \frac{P}{I_a^2} = R_B (1 - \delta). \tag{16}$$

  Where, $\delta = \frac{t_o}{T}$.
- Eq. 16 shows that the effective value of braking resistor can be changed steplessly from 0 to R_B as δ is controlled from 1 to 0.
- As the speed falls, δ can be increased steplessly to brake the motor at a constant maximum torque by chain-dotted line.

1 Chopper Control of Separately Excited dc Motors

2 Chopper Control of Series Motor

Chopper Control of Series Motor

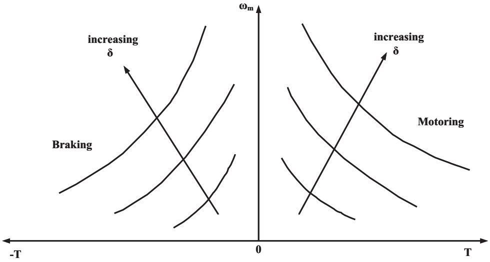


Figure 6. Motoring and regenerative braking characteristics of chopper controlled series motor.

Motoring

- Chopper circuit and v_a and i_a waveforms will be same as shown in Fig. 1.
- V_a is given by

$$V_a = \frac{1}{T} \int_0^{t_{on}} V\, dt = \delta V. \tag{17}$$

- However, e is not constant but varies with i_a.
- Due to saturation of magnetic circuit, relationship between e and i_a, is non-linear.
- The nature of speed torque curves is shown in Fig. 6.

Regenerative Braking

- With chopper control, regenerative braking of series motor can also be obtained.
- Power circuit of Fig. 2 (a) is employed.
- During regenerative braking, series motor functions as a self-excited series generator.
- For self-excitation, current flowing through field winding should assist residual magnetism.
- ∴ when changing from motoring to braking connection, while direction of armature current should reverse, field current should flow in the same direction.
- This is achieved by reversing the field with respect to armature when changing from motoring to braking operation.
- Waveforms of v_a and i_a will be same as those of Fig. 2 (b).

$$\omega_m = \frac{\delta V + I_a R_a}{K_a} \quad \text{and} \tag{18}$$

$$T = -K_a I_a. \tag{19}$$

- For a chosen value of I_a, K_a is obtained from magnetization characteristic.
- Then T and ω_m are obtained from Eqs. 19 and 18, respectively.
- The nature of speed-torque characteristics is shown in Fig. 6.
- Such characteristics give unstable operation with most loads.
- Consequently, regenerative braking of the series motor is difficult.

Dynamic Braking

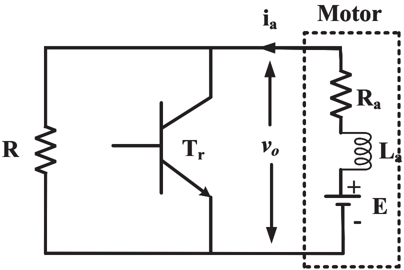


Figure 7. Dynamic braking of the separately excited motor by chopper control.

- Chopper circuit of Fig. 7 is used.
- Since the motor works as a self-excited generator, when changing from motoring to braking, field should be reversed.

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Thank You

Induction Motor Drives

Lecture-16

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1 Starting

2 Braking

Starting

Starting arrangement is chosen based on the load requirements and nature of supply (weak or stiff). It nay be required to have the following features:

- Motor should develop enough τ_{st} to overcome friction, τ_l and inertia of motor-load system, and thus, complete the staring process within a prescribed time limit.
- Starting current magnitude should be such that it does not cause the overheating of the machine and does not cause a dip in the source voltage beyond a permissible value.
- Usually, a motor draws 5 to 7 times rated current during starting.
- When load torque during starting and motor-load-inertia are not large, the starting process is over in a few seconds and therefore, motor temperature does not exceed the permissible value.
- In such applications, motor can always be started direct on line, provided the voltage dip caused by large starting current not beyond a permissible value.
- For small size motors voltage dip in the supply line is usually below acceptable level.
- When the motor is of large capacity and/or fed from a weak system some starting arrangement becomes necessary for reducing the starting current.
- In these applications it does not matter if the reduction in starting current is accompanied by a reduction in starting torque.

Starting

- When either the τ_l during starting is high or load inertia is large, the starting process takes long time.
- If motor carries large current during starting, it will get damaged due to overheating.
- $\therefore$ motor cannot be started direct on line.
- In these cases, those methods of starting which allow a decrease in starting current without a decrease in τ_{st} are employed.
- In some applications an increase in τ_{st} accompanied by a decrease in starting current may be required.
- In a squirrel-cage motor some measures for improvement of starting performance may be taken at design stage, as in case of high slip, deep-bar and double cage squirrel-cage motors.
- When needed, methods employed for starting squirrel-cage motors are:
  (1) Star-delta starter
  (2) Auto-transformer starter
  (3) Reactor starter
  (4) Saturable reactor starter
  (5) Part winding starter
  (6) ac voltage controller starter
  (7) Rotor resistance starter is used for starting of wound-rotor motor

Star-Delta Starter

- An induction motor designed to operate normally with delta connection is connected in star during starting.
- This allows reduction in stator voltage and current by $1/\sqrt{3}$.
- Since $\tau_m \propto V_t^2$, τ_{st} is reduced to one-third.
- Circuit breakers CB_m and CB_s are closed to start the machine with star connection.
- When steady-state speed is reached CB_s is opened and CB_r is closed to connect the machine in delta.

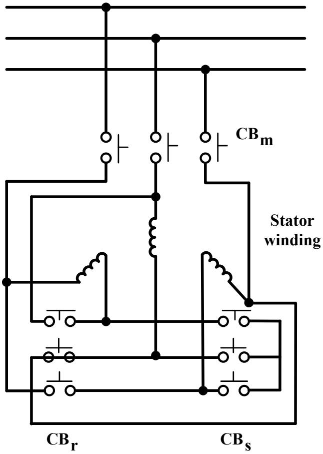

Figure 1. Circuit of Star-delta starting.

Auto-transformer Starter

- Reduced voltage for starting can also be obtained from an auto-transformer.
- For a secondary to primary turns ratio of a_T, motor terminal voltage and stator current are reduced by a_T.
- This reduces the current drawn from supply by a_T^2.
- Since $\tau \propto v_t^2$, it is also reduced by a_T^2.

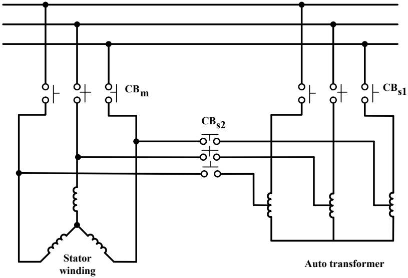

Figure 2. Open circuit transition of auto-transformer starting.

- After the motor has accelerated, it is connected to full supply voltage.
- An auto-transformer starter circuit is shown in Fig. 2 (a).
- First, CB_{s1} is closed followed by CB_{s2}.
- When motor has accelerated to full speed, CB_{s2} is opened and CB_m closed.
- Now CB_{s1} is opened to disconnect auto-transformer from the supply.

Closed Circuit Transition

- In both, star-delta and auto-transformer starting methods, changeover from low voltage to full voltage connection disrupts the flow of stator current and stator field collapses.
- Rotor current continues to flow due to its large time constant.
- Field produced by rotor currents induces voltages in the stator windings.
- Phase of the induced voltages is independent of supply voltages.

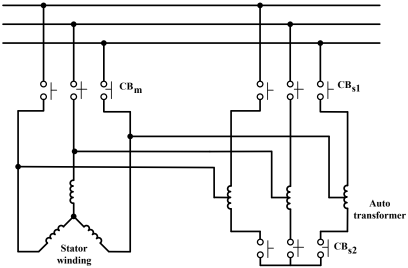

Figure 3. Closed circuit transition of auto-transformer starting.

Closed Circuit Transition

- A large current inrush is produced at the time of reconnection when induced and supply voltages are out of phase.
- When the current inrush is not acceptable, closed circuit transition is employed.
- A closed-circuit transition scheme for an auto-transformer starter is shown in Fig. 3 (b).
- It employs three circuit breakers: CB_{s1}, CB_{s2} and CB_m.
- First CB_{s2} is closed to close the star point connection of the auto-transformer. CB_{s1} is closed next.
- This completes low voltage connection of auto-transformer and the motor starts.
- After steady-state speed is reached, circuit breaker CB_{s2} is opened.
- Motor now runs with the upper part of auto-transformer phase windings in series with the stator.
- Windings simply function as series reactors.
- Now circuit breaker CB_m is closed, which bypasses series reactors and connects motor directly to the supply.
- At the beginning of starting alternatively, first CB_{s1} is closed instead of CB_{s2}.
- Then the motor and transformer will not produce magnetizing current surge simultaneously.

Reactor Starter

- I_{st} is reduced by connecting a three-phase reactor in series with stator.
- When the motor reaches full speed, the reactor is bypassed.
- CB_m is closed to start the machine.
- After full speed is reached CB_s is closed to short the reactor.
- It is advantageous to connect reactor at the neutral end of stator winding.
- This minimizes its voltage rating and also maintains its voltage and the voltage of breaker CB_s neutral potential during normal motor operation.

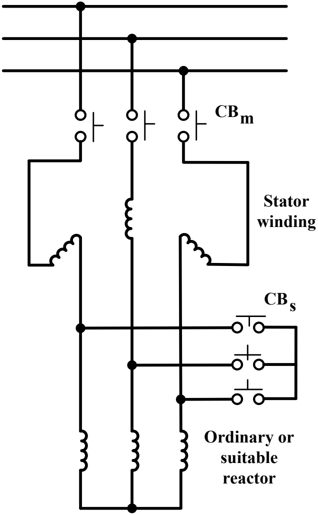

Figure 4. Circuit of reactor starting.

Soft Start using Saturable Reactor Starter

- In some applications τ_{st} must be controlled steplessly.
- For example in textile machines, it must be varied smoothly, otherwise fibre threads will break during starting.
- Such a starting arrangement is termed soft start.
- Thyristor voltage controller scheme is now widely used for soft start.
- A number of existing drives also employ saturable reactor starter in which a three-phase saturable reactor is connected in series with the stator.
- Saturable reactor has dc control winding.
- Reactance of saturable reactor can be varied steplessly by changing the control winding current.
- For starting, reactance is initially set at the highest value.
- τ_{st} is close to zero.
- Reactance is now reduced smoothly by increasing the control winding current.
- This gives stepless variation of τ_{st}.
- Consequently, the motor starts without any jerk and accelerates smoothly.

Unbalanced Starting Scheme for Soft Start

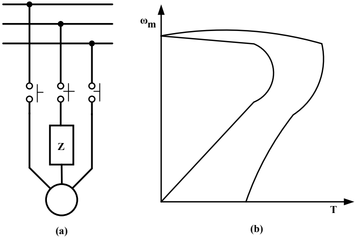

Figure 5. Starting with a single variable impedance in the stator.

- For soft start, a cheaper alternative shown in Fig. 5 (a), can also be employed.
- It consists of a variable impedance Z in one of the phases of machine.
- When impedance is very high, machine operates with single phasing and its speed-torque characteristic is similar to characteristic A of Fig. 5 (b), with a zero starting torque.
- When impedance is completely removed, speed torque curve is similar to the characteristic B, which is the natural characteristic of machine.
- For intermediate values of impedance, speed-torque curve will lie in between curves A and B.
- A smooth start, without a jerk, is achieved when impedance is controlled steplessly.
- The impedance may be a variable resistor or a single phase saturable reactor.

Part Winding Starting

- Some squirrel-cage motors have two or more stator windings which are connected in parallel during normal operation.
- During starting, only one winding is connected.
- This increases stator impedance and reduces starting current.
- Such a starting scheme is called part winding starting.
- Its implementation for a machine with two stator windings is shown in Fig. 6.
- Machine starts with winding 1 when CB_m is closed. After full speed is reached, CB_s is closed to connect winding 2.

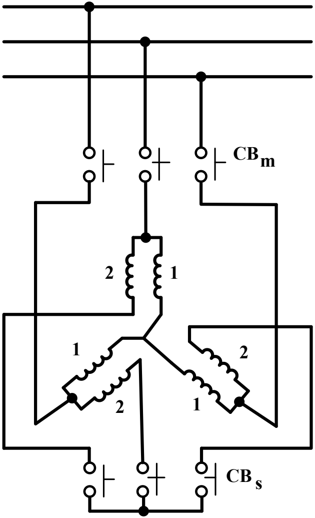

Figure 6. Circuit of part winding starting.

Rotor Resistance Starter

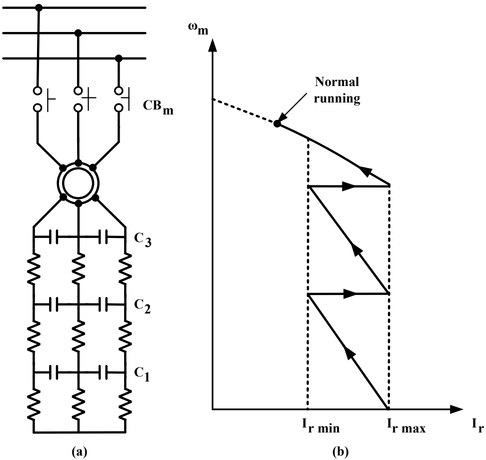

Figure 7. Rotor resistance starting.

Rotor Resistance Starter

- Wound-rotor motors are generally started by connecting external resistors in the rotor circuit (Fig . 7 (a)).
- The highest value of resistance is chosen to limit current at zero speed within the safe value.
- As the motor accelerates, sections in the external resistor are cut out one-by-one by closing contacts C_1, C_2 and C_3 so as to limit the rotor current between specified maximum and minimum values (Fig. 7 (b)).
- Since most of the rotor copper loss occurs in external resistors, rotor temperature rise during starting is substantially lower compared to other starting methods.
- Feature of this starting method → τ_{st} and torque-to-current ratio are high.
- Suitable for applications → requiring fast acceleration, frequent starts and stops, starting with heavy load, and starting with high inertia load.
- While τ_{max} is independent of rotor resistance value, the speed at which maximum torque is produced can be controlled by changing the value of external resistors.
- External resistors can therefore be varied to accelerate the machine at maximum torque.

Braking

The following methods are employed for braking of an induction motor:

- Regenerative braking
- Plugging or reverse voltage braking
- Dynamic (or rheostatic) braking further categorized as
  (a) ac dynamic braking
  (b) self-excited braking using capacitors
  (c) dc dynamic braking
  (d) zero sequence braking

Regenerative Braking

- The power input to an induction motor is given by

$$P_{in} = 3\, V\, I_s \cos\phi_s. \tag{1}$$

  Where, ϕ_s is the phase angle between stator phase voltage V and the stator phase current I_s.
- For motoring operation $\phi_s < 90°$.
- If the rotor speed becomes greater than synchronous speed, relative speed between the rotor conductors and air-gap rotating field reverses.
- This reverses the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns.
- Consequently, angle ϕ_s becomes greater than $90°$ and power flow reverses, giving regenerative braking.
- Magnetizing current required to produce air-gap flux is obtained from the source.
- The nature of speed-torque characteristic is shown in Fig. 8.
- When fed from a source of fixed frequency, regenerative braking is possible only for speeds greater than synchronous speed.

Regenerative Braking

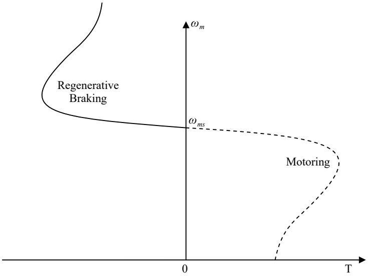

Figure 8. Speed-torque characteristics during regenerative braking.

- With a variable frequency source, it can also be obtained for speeds below synchronous speed.
- When regenerative braking employed for holding motor-speed against an active load, stable operation generally possible between synchronous speed and the speed for which braking torque is maximum.
- Main advantage of regenerative braking is that generated power is usefully employed and drawback being that when fed from a constant frequency source, it cannot be employed below synchronous speed.
- The utilization (or absorption) of regenerated power occurs in the same way for regenerative braking of dc motors.

Plugging or Reverse Voltage Braking

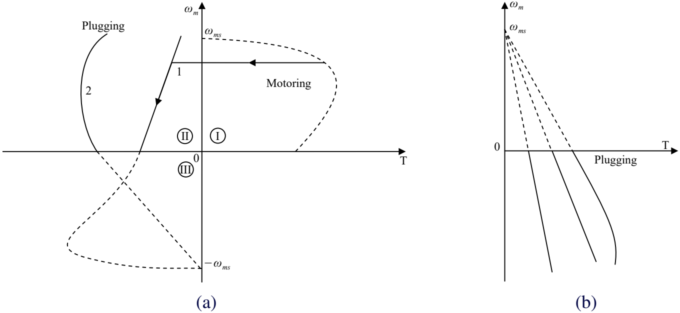

Figure 9. Plugging (a) 1: natural characteristic, 2: with external resistance in rotor and (b) plugging in IV quadrant with large external resistance in rotor.

- When phase sequence of supply of the motor running at a speed is reversed, by interchanging connections of any two phases of stator with respect to supply terminals, operation shifts from motoring to plugging as shown in Fig. 9.
- Plugging characteristics are actually extension of motoring characteristics for negative phase sequence from quadrant III to II.
- Reversal of phase sequence reverses the direction of rotating field.

Plugging or Reverse Voltage Braking

- If the slip for plugging is denoted by s_n, then

$$S_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = 2 - s. \tag{2}$$

- Motor performance can be calculated, when s is replaced by s_n $(2 - s)$.
- Since at the instant of switchover to plugging, slip can be upto 2, the rotor induced can be twice of case of wet speed.
- Consequently, motor current is large, although braking torque is low.
- In case of wound-rotor motors, a resistance equal to twice the starter resistance is inserted in the rotor current to starting value.
- This also increases braking torque as shown by curve 2 ($Fig.9$).
- As shown in Fig. 9, torque is not zero at zero speed.
- When used for stopping motor, it is necessary that the motor should be disconnected from supply at or near zero speed.
- This makes it necessary to use an additional device for detecting zero speed and disconnecting motor from supply.

Plugging or Reverse Voltage Braking

- This braking is suitable for reversing the motor.
- As motor is already connected for operation in reverse direction and torque is not zero at zero or any other speed, motor smoothly decelerates and then accelerates in the reverse direction.
- A special case of plugging occurs when an induction motor connected to positive sequence voltages is driven by an active load in the reverse direction (quadrant IV).
- Crane hoist is one such application. A large rotor resistance is employed so that the characteristics have a negative slope, and thus, drive is steady-state stable (Fig. 9 (b)).
- In this method, mechanical energy supplied to the rotor, either by active load or from kinetic energy stored in motor and load inertia, is converted into electrical energy and wasted in rotor resistance.
- Additional energy is taken from the source and wasted in rotor resistance. When braked under no load from synchronous speed, total amount of energy dissipated in rotor resistance given by $(3/2)\,J\,\omega_{ms}^2$ which is three times the energy stored in inertia.
- Thus, an additional energy equal to $J\,\omega_m^2$ is taken from the source.

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Thank You

Induction Motor Drives

Lecture-17

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1 Dynamic or Rheostatic Braking

2 Self-Excited Braking using Capacitors

3 dc Dynamic Braking

4 Zero Sequence Braking

ac Dynamic Braking

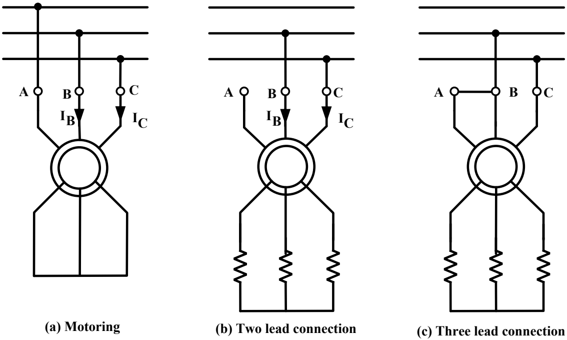


Figure 1. ac dynamic braking of a wound rotor motor.

- ac dynamic braking is obtained when the motor is run on a single phase supply by disconnecting one phase from the source and either leaving it open (Fig. 1 (b)) or connecting it with another machine phase (Fig. 1 (c)).
- The two connections of Fig. 1 (b) and (c) are, respectively, known as two and three lead connections.

ac Dynamic Braking

- When connected to a 1-phase supply, the motor can be considered to be fed by positive and negative sequence three-phase set of voltages.
- Net torque produced by the machine is sum of torques due to positive and negative sequence voltages.
- When rotor has a high resistance, the net toruqe is negative and braking operation is obtained.

The motor analysis for two and three lead connections is done as follows:

- Two lead connection: Assume that phase A of Y-connected motor is open circuited.
- Then $\overline{I}_A = 0$ and $\overline{I}_c = -\overline{I}_B$.
- Hence, positive and negative sequence components overline $\overline{I}_p$ and $\overline{I}_n$, respectively are given by

$$\overline{I}_p = \frac{1}{3}\left(\overline{I}_A + \alpha\overline{I}_B + \alpha^2\overline{I}_C\right) = \frac{1}{3}\left(0 + \alpha\overline{I}_B - \alpha^2\overline{I}_B\right) = j\overline{I}_B/\sqrt{3}. \quad (1)$$

$$\overline{I}_n = \frac{1}{3}\left(\overline{I}_A + \alpha^2\overline{I}_B + \alpha\overline{I}_C\right) = \frac{1}{3}\left(0 + \alpha^2\overline{I}_B - \alpha\overline{I}_B\right) = -j\overline{I}_B/\sqrt{3}. \quad (2)$$

Where, α is given by $\alpha = e^{j\,120^\circ} = cos\,120^\circ + j\,sin\,120^\circ$.

ac Dynamic Braking

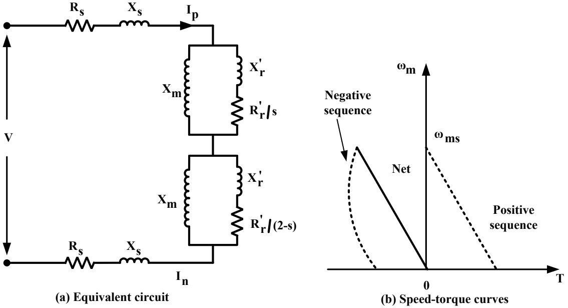


Figure 2. ac dynamic braking with two lead connection.

- As positive and negative sequence components are equal and opposite, two equivalent circuits can be connected in series opposition.
- Voltage to be applied to this series combination will be

$$\bar{V}_p - \bar{V}_n = \frac{1}{3}\left(\bar{V}_A + \alpha\,\bar{V}_B + \alpha^2\,\bar{V}_C\right) - \frac{1}{3}\left(\bar{V}_A + \alpha^2\,\bar{V}_B + \alpha\,\bar{V}_C\right)$$

$$= \frac{1}{3}\left(\alpha - \alpha^2\right)\left(\bar{V}_p - \bar{V}_n\right) = \frac{1}{3}(j\sqrt{3})\,(\bar{V}_{BC}) = j\,\bar{V}_{BC}/\sqrt{3}. \qquad (3)$$

ac Dynamic Braking

- With an applied voltage $j\,V_{ac}/\sqrt{3}$ if current is $I_p = -I_n = j\,I_B/\sqrt{3}$, it follows that with an applied phase voltage V the current would be $I_B/(\sqrt(3))$.
- Equivalent circuit may therefore be drawn as shown in Fig. 3 (a).
- Although the values of positive and negative sequence components of current are equal, the corresponding torques are not.
- The nature of speed-torque curves for positive and negative sequence currents, and net torque are shown in Fig. 6.16 (b).
- By suitable choice of rotor resistance, braking torque can be obtained in the entire speed range.
- As the rotor resistance required is large, ac dynamic braking can only be used in wound-rotor motors.
- In this connection at high speeds (or at low values of slip), the impedance of positive sequence component part becomes very high.
- As positive and negative sequence components of current have to be equal, net braking torque is small, and therefore, braking is not very effective.

ac Dynamic Braking

- Here, two phases of Y-connected motor winding are connected in parallel in series with the third phase (Fig. 1 (c)).
- Let phases A and B be connected together, then

$$\bar{V}_{AB} = 0, \bar{V}_{BC} = \sqrt{3}\,V \text{ and} \bar{V}_{CA} = -\sqrt{3}\,V.$$

- Hence,

$$\bar{V}_p\,(\text{line}) = \left(\bar{V}_{AB} + \alpha\,\bar{V}_{BC} + \alpha^2\,\bar{V}_{CA}\right)/3.$$

$$= \left(0 + \alpha\sqrt{3}\,V - \alpha^2\sqrt{3}\,V\right)/3 = j\,V. \tag{4}$$

$$\bar{V}_n\,(\text{line}) = \left(\bar{V}_{AB} + \alpha^2\,\bar{V}_{BC} + \alpha\,\bar{V}_{CA}\right)/3(5)$$

$$= \left(0 + \alpha^2\sqrt{3}\,V - \alpha\sqrt{3}\,V\right)/3 = -j\,V \tag{6}$$

$$V_p\,(\text{phase}) = V_n\,(\text{phase}) = \frac{V}{\sqrt{3}}. \tag{7}$$

ac Dynamic Braking

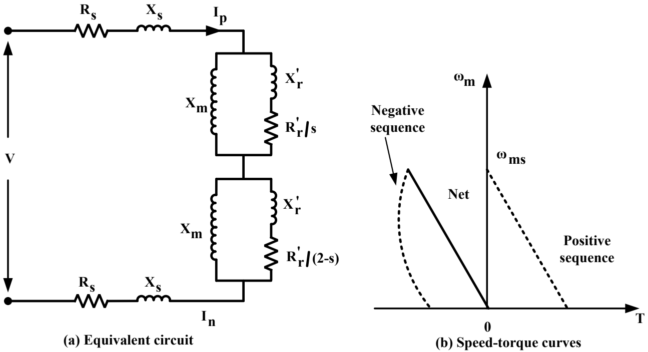


Figure 3. Equivalent circuit for three lead connection.

ac Dynamic Braking

- In contrast to two lead connection, here magnitude of positive and negative sequence components of voltage are equal and not the positive and negative sequence components of currents.
- Positive and negative sequence parts of the circuit are independent, and therefore, there is no restriction imposed on negative sequence component of current by positive sequence part of equivalent circuit.
- Thus higher braking torques are obtained (compared to two lead connection) at high speeds.
- The speed-torque characteristic with this connection is the same as shown in Fig. 1 (b).
- Any inequality between the contact resistances in connections of two paralleled phases reduces the braking torque and can even lead to motoring torque, as the condition tends more towards two lead connection with increasing resistance in one of the two phases (as rotor resistance employed is less than the two lead connection).
- Therefore, two lead connection is generally preferred in spite of its low torque.
- Main application of single-phase ac braking is in crane hoist.

1 Dynamic or Rheostatic Braking

2 Self-Excited Braking using Capacitors

3 dc Dynamic Braking

4 Zero Sequence Braking

Self-Excited Braking using Capacitors

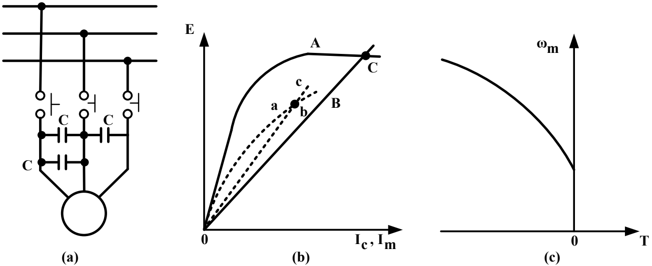


Figure 4. Self-excited braking of induction motor.

- In this method three capacitors are kept permanently connected across the motor terminals.
- Values of capacitors is so chosen that when disconnected from the line, motor works as a self- excited induction generator.

Self-Excited Braking Using Capacitors

- Braking connection is shown in Fig. 4 (a) and self-excitation process is explained in Fig. 4 (b) for no load condition.
- Curve A is no load magnetization curve of the machine at a given speed, and line B represents the current through capacitors, given by

$$I_c = \sqrt{3}E/X_c = \sqrt{3}E\,\omega\,C. \tag{8}$$

Where, E is the stator induced voltage per phase.

- Capacitors supply the necessary reactive current for excitation. Operation occurs at point C which is the inter-section of two characteristics.
- When speed falls, value of E for the same magnetization current falls and the new magnetization characteristic a is obtained.
- On the other hand, the slope of E versus I_c, characteristic increases, giving new characteristic b.
- Intersection of two curves now occurs at c.

Self-Excited Braking Using Capacitors

- Thus, reduction in speed while shifts the magnetization curves downward, slope of capacitor voltage vs current curve increases.
- At certain critical speed, which is usually high, two curves fail to intersect and the machine therefore does not self-excite and braking torque falls to zero.
- Speed-torque characteristic under self-excited braking is shown in Fig 4 (c).
- Sometimes external resistors are connected across stator terminals to increase braking torque and to dissipate some generated energy outside the machine.
- Construction of Fig. 4 (b) is valid only for no-load operation.
- For more accurate analysis, motor impedance drops should be considered.
- This scheme is rarely used, as braking torque drops to zero at a speed which is usually high.

1 Dynamic or Rheostatic Braking

2 Self-Excited Braking using Capacitors

3 dc Dynamic Braking

4 Zero Sequence Braking

dc Dynamic Braking

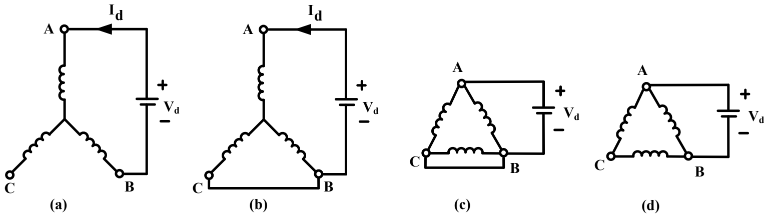


Figure 5. Various stator connections for dc dynamic braking: (a) and (d) are two lead connections and (b) and (c) are three lead connections.

- It is obtained when the stator of an induction motor running at a speed is connected to a dc supply.
- Two commonly used connections, two and three lead, for star and delta-connected stators are shown in Fig. 5.

dc Dynamic Braking

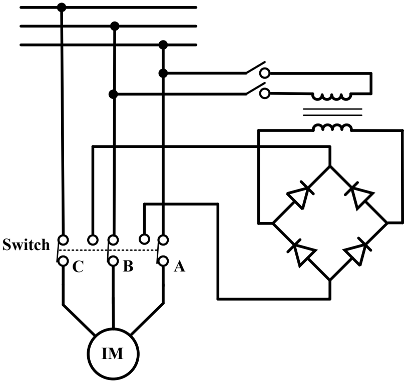


Figure 6. Detalis of two lead dc dynamic braking connection.

- A method of getting dc supply with the help of a diode bridge for two lead connection is shown in Fig. 6.
- dc current flowing through the stator produces a stationary magnetic field.
- Motion of rotor in this field induces voltage in the rotor winding.
- Machine, therefore, works as a generator. Generated energy is dissipated in the rotor circuit resistance, thus giving dynamic braking.

dc Dynamic Braking

- As the field is stationary, the relative speed between rotor conductors and the field is now ω_m.
- Frequency of induced voltage will be equal to the frequency of ac source voltage (or rated motor frequency when $omega_m = \omega_{ms}$.
- Let voltage induced in the rotor when running at a synchronous speed be E_r.
- When running at a speed ω_m the induced voltage and its frequency will be $s\,E_r$ and $s\,f$, respectively. Then

$$s = \frac{\omega_m}{\omega_{ms}} = \frac{(1 - s)\,\omega_{ms}}{\omega_{ms}} = (1 - s). \tag{9}$$

- This yields per phase equivalent circuit of Fig. 7 (a) for the rotor.
- Dividing all quantities by S will yield an equivalent circuit at the rated frequency.

dc Dynamic Braking

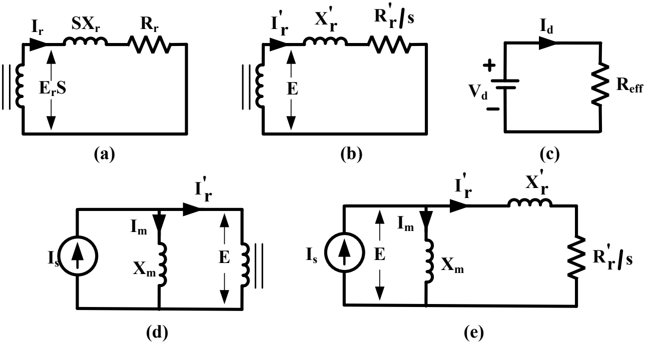


Figure 7. Derivation of dc dynamic braking equivalent circuit. (a) and (b) are rotor equivalent circuits, (c) and (d) are stator equivalent circuits and (e) is the complete equivalent circuit.

- Referring various parameters of equivalent circuit so obtained to stator turns gives per phase equivalent circuit of the rotor shown in Fig. 7 (b).
- The equivalent circuit of stator under dc dynamic braking is shown in Fig. 7 (c).
- In order to combine with rotor equivalent circuit of Fig. 7 (b) we should first obtain per phase equivalent circuit of the stator at rated frequency.

dc Dynamic Braking

- Equivalent circuit Fig. 7 (c) suggests that the stator mmf is constant and independent of speed.
- $\therefore$ imagine stator to be fed by a three-phase balanced current source of rated frequency giving a phase current I_s.
- The ac current I_s will be equivalent to I_d provided it produces stator mmf of same amplitude as the dc current I_d.
- Thus, we are replacing a stationary stator mmf produced by dc current I_d by a mmf (produced by I_s) of identical amplitude but revolving at synchronous speed.
- Difference of these two mmfs will be air-gap mmf which will be responsible for producing air-gap flux which in turn cause voltage E of rated frequency to be induced in the stator.
- Per phase equivalent circuit of stator at rated frequency thus takes the form shown in Fig. 7 (d).
- Combining equivalent circuits of Fig. 7 (b) and (d) and removing the transformer gives rated frequency per phase equivalent circuit (Fig. 7 (e)).

dc Dynamic Braking

- I_r' is small for small s, and therefore, I_m approaches I_s.
- Because of large value of I_m, the magnetic circuit gets saturated.
- Thus, X_m is not constant but varies with I_m.
- For accurate analysis, variation of X_m with I_m must be taken into account.
- Relationship between I_s and I_d depends on the stator connection.
- As an example let us derive it for the two lead connection of Fig. 5 (a).
- Here $I_A = I_d$ and $I_B = -I_d$.
- If N is effective number of turns in each winding then peak mmf produced by phase A will be $I_d N$ and the peak mmf produced by phase B will be $(-I_d N)$.
- Assuming these mmfs to be sinusoidally distributed in space, peak of the resultant mmf will be

$$\begin{aligned} F &= \left[F_A^2 + F_B^2 + 2\,F_A\,F_B \cos 120^\circ\right]^{1/2} \\ &= \left[(I_d\,N)^2 + (-I_d\,N)^2 + 2\,(I_d\,N)\,(-I_d\,N)\,(-0.5)\right]^{1/2} \\ &= \sqrt{3}\,I_d\,N. \end{aligned} \tag{10}$$

dc Dynamic Braking

- When machine is fed by a balance thre–phase current source I_s, peak of stator mmf is

$$F^{'} = \frac{3}{2}\,(\sqrt{2}\,I_s)\,N \tag{11}$$

- I_s will be equivalent of I_d when $F = F^{'}$. Therefore from Eqs. 10 and 11

$$I_s = \sqrt{\frac{2}{3}}\,I_d. \tag{12}$$

- Values of I_s for other connections are $I_d/\sqrt{2}$; $I_d/\sqrt{6}$ and $\sqrt{2}\,I_d/3$.
- The speed-torque characxtristic is calculated as follows.
- From equivalent circuit of Fig. 7 (e)

$$E = I_m\,X_m \tag{13}$$

$$E^2 = I_r^{'}\left[\left(\frac{R_r^{'}}{s}\right)^2 + X_r^{'\,2}\right]. \tag{14}$$

- Consider distribution of currents between parallel branches formed by X_m and the rotor

$$I_s^2\,X_m^2 = I_r^{'\,2}\left[\left(\frac{R_r^{'}}{s}\right)^2 + (X_r^{'\,2} + X_m)^2\right] \tag{15}$$

dc Dynamic Braking

- Substracting Eq. 14 from 15 yields

$$I_r'^2 = \frac{I_s^2 - I_m^2}{1 + \frac{2X_r'}{X_m}} \tag{16}$$

- From Eq. 14

$$s = \frac{R_r'}{\left[(E/I_r')^2 - X_r'^2\right]^{1/2}} \tag{17}$$

- The motor torque is

$$T = \frac{3}{\omega_{ms}}(I_r'^2 R_r'/s). \tag{18}$$

- Since X_m is a function of I_m Eqs. 13 - 17 are non-linear algebraic equations.
- Use of the following steps avoids the need for a numerical solution.
- Assume a value of I_m obtain corresponding E from magnetization characteristic, calculate X_m from Eq. 13, obtain I_r' from 16, calculate s from Eq. 16 and then ω_m and T from Eqs. 9 and 18, respectively.
- Fig. 8 Shows the nature of speed torque curves for two values of rotor resistance.

dc Dynamic Braking

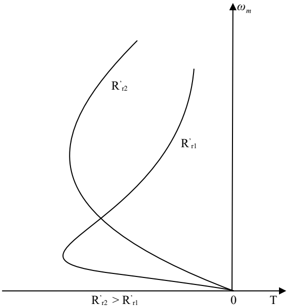
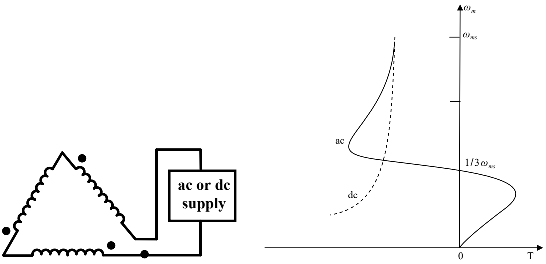


Figure 8. dc dynamic braking speed torque curves.

- In a squirrel-cage motor or a wound-rotor motor without an external resistance in rotor, the maximum torque occurs at low speed.
- While maximum torque is independent of rotor resistance, speed at which the maximum torque fast braking is required, a sectionalised resistance is connected in rotor circuit and it is cut-out as speed falls.
- When used to hold an active load, as in mine winders, a large resistance is connected to obtain speed-torque curves with a negative slope, in order to ensure steady-state stability.

Zero Sequence Braking



(a) (b)

Figure 9. Zero-sequence braking.

- In this braking, three stator phases are connected in series across either a single phase ac or a dc source as shown in Fig. 9 (a).
- Such a connection is known as a zero-sequence connection, because currents in all the stator windings are co-phasal.
- The mmf caused by co-phasal (or zero-sequence) currents produces a magnetic field having three times the number of poles for which the machine is actually wound.
- With an ac supply, the resultant field is stationary in space and pulsates at the frequency of supply.

Zero Sequence Braking

- With dc supply, resultant field is stationary in space and is of constant magnitude.
- An important advantage of this connection is the uniform loading of all stator phases.
- The nature of speed-torque curves for ac and dc supply is shown in Fig. 9 (b).
- With ac supply, braking could be used only up to one-third of synchronous speed.
- However, braking torques produced by this connection are considerably larger than motoring.
- Motor essentially works in regenerative braking.
- For motors with low rotor resistance, a significant part of the generated energy is recovered.
- Unlike ac dynamic braking, it does not require large rotor resistance and can be used with squirrel cage and would-rotor motors.
- With dc supply, braking is available in the entire speed range.
- It is essentially a dynamic braking as all the generated energy is wasted in rotor resistances.
- Switching arrangement, from normal three-phase to zero sequence operation, is extremely simple when motor has a delta-connected stator.

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Thank You

Induction Motor Drives

Lecture-18

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1. Transient Analysis
2. Voltage Source Inverter (VSI) Control

Transient Analysis

- Analysis of transient operating conditions of a drive → starting, braking, load changing, speed changing, etc.
- A rigorous analysis of transient operation of an induction motor drive, can be done only by the d-q axis model involving long Calculations.
- A simple method of analysis, with satisfactory accuracy for most applications is chained by using steady-state torque relations.
- Such an analysis is based on the assumption that electrical time constants can be neglected, as they are very small compared to mechanical time constant.
- Thus, we can write following equation for transient operation of an induction motor drive,

$$J = \frac{d\,\omega_m}{dt} = \tau(\omega_m) - \tau_l(\omega_m). \tag{1}$$

- Eq. 1 can be evaluated graphically to obtain ω_m versus t curve, and energy losses in motor and external rotor resistance.

Starting and Plugging

- For starting and plugging operation of machine, torque is given by Eq. 2.

$$\frac{\tau}{\tau_{max}} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}} \tag{2}$$

- Substituting from Eq. 2 into 1 yields,

$$J\,\frac{d\,\omega_m}{dt} = \frac{2\,\tau_{max}}{\frac{s}{s_m} + \frac{s_m}{s}} - \tau_l(\omega_m). \tag{3}$$

- In some cases, Eq. 3 will be in integral form, and therefore, can be solved analytically.
- It is useful to examine the transients for starting and plugging operations when operating on no-load. Thus, from Eq. 3 for no-load operation

$$J\,\frac{d\,\omega_m}{dt} = \frac{2\,\tau_{max}}{\frac{s}{s_m} + \frac{s_m}{s}}. \tag{4}$$

- Differentiating $\omega_m = \omega_{ms}\,(1 - s)$ gives

$$J\,\frac{d\,\omega_m}{dt} = -\,\omega_{ms}\,\frac{ds}{dt}. \tag{5}$$

Starting and Plugging

- Substituting from Eq. 5 into 4 and rearranging the terms

$$dt = -\frac{\tau_m}{2}\left(\frac{s_m}{s} + \frac{s}{s_m}\right) ds. \qquad (6)$$

  Where, $\tau_m = \frac{j\,\omega_{ms}}{\tau_{max}}$.

- τ_m is the mechanical time constant of motor. Is is defined as the time taken by motor to reach its synchronous speed from standstill under constant accelerating torque equal to the maximum torque of motor.
- From Eq. 6, time required to start an induction motor on no load is

$$t_s = -\frac{\tau_m}{2}\int_1^{0.05}\left(\frac{s}{s_m} + \frac{s_m}{s}\right) ds. \qquad (7)$$

- When operating on load, steady-state is reached when $s = 0$. item Thus, during the starting slip, changes from 1 to 0.

Starting and Plugging

- However, if Eq. 7is integrated for $s = 1$ to $s = 0$ an infinite value is obtained for starting time.
- When final speed is the steady-state equilibrium speed, transients are considered to be over when 95 % range of speed is covered.
- ∴ in Eq. 7 integration is done from $s = 1$ to $s = 0.05$. Solving Eq. 7 gives

$$t_s = \tau_m \left[\frac{1}{4\, s_m} + 1.5\, s_m \right]. \tag{8}$$

- Thus starting time is a function of s_m.
- Starting time has a minimum value of $1.22\tau_m$ at $s_m = 0.4$.
- From Eq. $s_m = \pm \frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}}$, when R_s is negligible, rotor resistance required to start the motor in minimum time is

$$(R_{rm}')_s = 0.4\,(X_s + X_r'). \tag{9}$$

Starting and Plugging

- From Eq. 6, time required for stopping by plugging, when initially running at synchronous speed, can be expressed as

$$t_b = -\frac{\tau_m}{2}\int_1^2 \left(\frac{s}{s_m} + \frac{s_m}{s}\right) ds = \tau_m\left[0.345\, s_m + \frac{0.75}{s_m}\right]. \qquad (10)$$

- Stopping time is again a function of s_m. It has a minimum value of $1.027\tau_m$ at $s_m = 1.47$.
- Corresponding value of rotor resistance is

$$(R'_{rm})_b = 1.47\,(X_s + X'_r). \qquad (11)$$

- Similarly, from Eq. 6, time required for speed reversal by plugging when running on no load is given by

$$t_r = -\frac{\tau_m}{2}\int_2^{0.05} \left(\frac{s}{s_m} + \frac{s_m}{s}\right) ds = \tau_m\left[3.69\, s_m + \frac{1}{s_m}\right]. \qquad (12)$$

- Minimum time for reversal is thus $2.88\tau_m$ and corresponding value of s_m is 0.52.
- Rotor resistance required for speed reversal by plugging in minimum time is

$$(R'_{rm})_r = 0.52\,(X_s + X'_r). \qquad (13)$$

Calculation of Energy Losses

- The rotor winding loss for starting can be written as

$$E_{sr} = \int_0^{t_s} 3\, I_r'^2\, R_r'\, dt. \tag{14}$$

- Substituting from Eqs. $P_g = 3\, I_r'^2\, R_r'/s$ and $T = P_g/\omega_{ms}$ gives

$$E_{sr} = \int_0^{t_s} \omega_{ms}\, T\, s\, dt. \tag{15}$$

- As the machine is operating under no load

$$J\, \frac{d\ \ m}{dt} = T. \tag{16}$$

- Substituting from Eq. 5

$$\begin{aligned} -J\, \omega_{ms}\, \frac{ds}{dt} &= T \\ T\, dt &= -J\, \omega_{ms}\, ds. \end{aligned} \tag{17}$$

- Substituting in Eq. 15 gives

$$E_{sr} = -\int_1^{0} J\, \omega_{ms}^2\, s\, ds = \frac{1}{2}\, J\, \omega_{ms}^2. \tag{18}$$

Calculation of Energy Losses

- It is interesting to note that rotor winding energy loss is equal to the kinetic energy stored in moving parts at completion of the starting process, and it is independent of the starting time or rotor resistance.
- However, if an external resistance is connected in rotor circuit only a part of this loss is used to heat the motor.
- Energy loss in stator winding, neglecting magnetizing current is

$$E_{ss} = \int_0^{t_s} I_r'^2 R_s \, dt \tag{19}$$

$$= \frac{1}{2} J \omega_{ms}^2 \left(\frac{R_s}{R_r'} \right) \tag{20}$$

- Hence, total winding loss during starting under no load is

$$E_s = \frac{1}{2} J \omega_{ms}^2 \left(1 + \frac{R_s}{R_r'} \right). \tag{21}$$

- Proceeding similarly, rotor winding loss during stopping by plugging under no load can be written as

$$E_{sr} = \int_2^1 J \omega_{ms}^2 s \, ds = \frac{3}{2} J\, {}^2_{ms}. \tag{22}$$

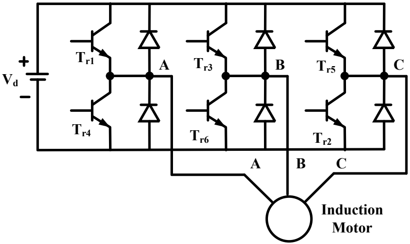
Calculation of Energy Losses

- Eq. 18 suggests that rotor winding loss can be reduced when started by using methods based on the variation of synchronous speed.
- As an example let us consider a motor with an arrangement for doubling the pole number.
- Let it be started with higher pole number for which the synchronous speed is $\omega_{ms}/2$. item Then, from Eq. 18 rotor copper loss for change of speed from 0 to $\omega_{ms}/2$ will be $J\,\omega_{ms}^2/8$.
- Now, the pole numbered is lowered. Consequently, rotor copper loss for speed range $\omega_{ms}/2$ to ω_{ms} will be

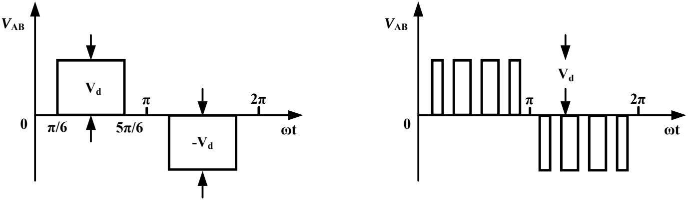
$$E'_{sr} = \int_{0.5}^{0} J\,\omega_{ms}^2\, s\, ds = \frac{J\,\omega_{ms}^2}{8}. \tag{23}$$

- Thus, total rotor winding loss is $J\,\omega_{ms}^2/4$, which is one-half of the copper loss when there is no provision for doubling the pole number.

Voltage Induction Motor Drives



(a) Transistor inverter-fed induction motor drive



(b) Stepped waveform inverter line voltage waveform

(c) PWM inverter line voltage waveform

Figure 1. VSI fed induction motor drives.

Voltage Induction Motor Drives

- Variable frequency and variable voltage supply for induction motor control can be obtained either from a voltage source inverter (VSI) or a cycloconverter.
- Fig. 1 (a) shows a VSI employing transistors.
- Any other self-commutated device can be used instead of a transistor.
- Generally MOSFET is used in low voltage and low power inverters, IGBT (insulated gate bipolar transistor) and power transistors are used up to medium power levels and GTO (gate turn off thyristor) and IGCT (insulated gate commutated thyristor) are used for high power levels.
- VSI can be operated as a stepped wave inverter or a pulse-width modulated (PWM) inverter.
- When operated as a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of $T/6$ and each transistor is kept on for the duration $T/2$, where T is the time period for one cycle.
- Resultant line voltage waveform is shown in Fig. 1 (b).

Voltage Induction Motor Drives

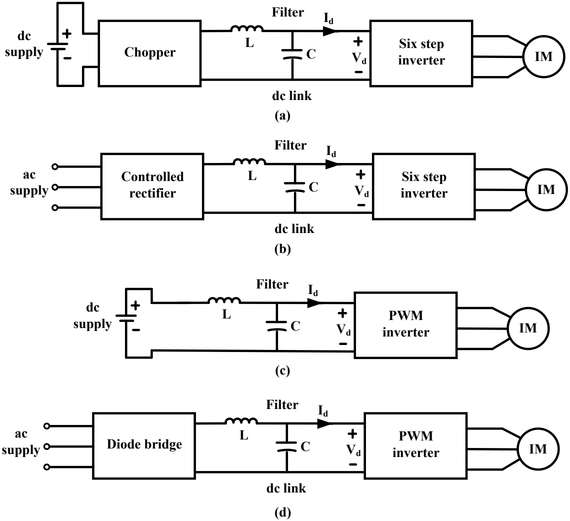


Figure 2. VSI controlled induction motor drives.

Voltage Induction Motor Drives

- Frequency of inverter operation is varied by varying T and the output voltage of the inverter is varied by varying dc input voltage.
- When supply is dc, variable dc input voltage is obtained by connecting a chopper between dc supply and inverter (Fig. 2 (a)).
- When supply is ac, variable dc input voltage is obtained by connecting a controlled rectifier between ac supply and inverter (Fig. 2 (b)).
- A large electrolytic filter capacitor C is connected in dc link to make inverter operation independent of rectifier or chopper and to filter out harmonics in dc link voltage.
- Inverter output line and phase voltages are given by the following Fourier series

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[sin\,\omega t - \frac{1}{5} sin\,5\,\omega t - \frac{1}{7} sin\,7\,\omega t + \frac{1}{11} sin\,11\,\omega t + \frac{1}{13} sin\,13\,\omega t ... \right] \tag{24}$$

$$V_{AN} = \frac{2}{\pi} V_d \left[sin\,\omega t + \frac{1}{5} sin\,5\,\omega t + \frac{1}{7} sin\,7\,\omega t \right] \tag{25}$$

Voltage Induction Motor Drives

- The rms value of the fundamental phase voltage is given as

$$V = \frac{\sqrt{2}}{\pi} V_d. \tag{26}$$

- The main drawback of the stepped wave inverter is the large harmonics of low frequency in the output voltage.
- Consequently, an induction motor drive fed from a stepped wave Inverter suffers from the following drawbacks:
- (a) Because of low-frequency harmonics, the motor losses are increased at all speeds, causing derating of the motor.
- (b) Motor develops pulsating torques due to fifth, seventh, eleventh and thirteenth harmonics which cause jerky motion of the rotor at low speeds.
- (c) Harmonic content in motor current increases at low speeds. The machine saturates at ligh loads at low speeds due to high (V/f) ratio.
- These two effects overheat the machine at low speeds, thus limiting lowest speed to around 40 % of base speed.
- Harmonics are reduced, low-frequency harmonics are eliminated, associated losses are reduced and smooth motion is obtained at low speeds also when inverter is operated as a pulse-width modulated inverter.

Voltage Induction Motor Drives

- Fig. 1 (c) shows output voltage waveform for sinusoidal pulse-width modulation.
- Since output voltage can now be controlled by pulse-width modulation, no arrangement is required for the variation of input dc voltage.
- Hence, the inverter can be directly connected when the supply is dc [Fig. 2 (c)] and through a diode rectifier when supply is ac. [Fig. 2 (d)).
- The fundamental component in the output phase voltage of a PWM inverter operating with sinusoidal PWM is given by

$$V = m\frac{V_d}{2\sqrt{2}}. \tag{27}$$

  Where, m is the modulation index.
- The harmonics in the motor current produce torque pulsation and derate the motor.
- For a given harmonic content in motor terminal voltage, the current harmonics are reduced when the motor has higher leakage inductance, this reduces derating and torque pulsations.
- ∴ when fed from VSI, induction motors with large (compared to when fed from the sinusoidal supply) leakage inductance are used.

Braking and Multiquadrant Opeartion of VSI Induction Motor Drives

- The power into the motor is given by

$$P_{in} = 3\, V\, I_s \cos\phi. \tag{28}$$

Where, V and I_s are fundamental components of the motor phase voltage and current, respectively. ϕ is the phase angle between V and I_s.

- In motoring operation $\phi < 90^\circ$, therefore P_{in} is positive i.e., power flows from the inverter to the machine.
- A reduction in frequency makes the synchronous speed less than the rotor speed and the relative speed between the rotor conductors and air-gap rotating field reverses.
- This reveries the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns.
- Consequently, angle ϕ becomes greater than 90° and power flow reverses.
- The machine works as a generator feeding power into the inverter, which in turn feeds power into dc link by reversing the dc link current I_d.
- Regenerative braking is obtained when the power flowing from the inverter to the dc link is usefully employed and dynamic braking is obtained when it is wasted in a resistance.

Dynamic Braking

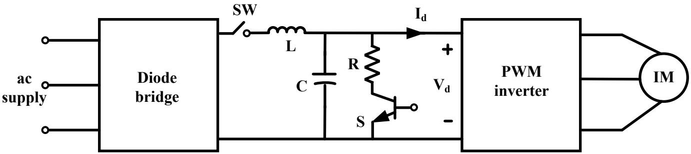


Figure 3. Dynamic braking of VSI controlled IM drives.

- Consider the dynamic braking of pulse-width modulated inverter drive of Fig. 2 (d).
- With dynamic braking the drive will be as shown in Fig. 3.
- For dynamic braking, switch SW and a self-commutated switch (here transistor) in series with braking resistance R_B connected across the dc link are added to the drive of Fig. 2 (d).

Dynamic Braking

- When operation of the motor is shifted from motoring to braking switch SW is opened.
- Generated energy flowing into the dc link charges the capacitor and its voltage rises.
- When it crosses a set value, switch S is closed, connecting the resistance across the link.
- The generated power and a part of energy stored in the capacitor flow into the resistance, and dc link voltage reduces.
- When it falls to its nominal value, S is opened.
- Thus by closing and opening switch S based on the value of dc link voltage, generated energy is dissipated in the resistance, giving dynamic braking.
- The dynamic braking operation of the drives of Fig. 2 (a) to (c) can be obtained similarly.

Regenerative Braking

- Consider the regenerative braking of pulse-width modulated (PWM) inverter drives of Fig. 2 (c) and (d).
- In the drive of Fig. 2 (c) when machine operation shifts from motoring to braking, I_d reverses and flows into the dc supply feeding the energy to the source.
- Thus, the drive of Fig. 2 (c) already has regenerative braking capability.
- In the case of the drive of Fig. 2 (d), for regenerative braking, the power supplied to the dc link must be transferred to the ac supply.
- When the operation shifts from motoring to braking reverses but v_d remains in the same direction.
- Thus for regenerative braking capability, a converter capable of dealing with dc voltage of one polarity and dc current of either direction is required.
- The recent drives use synchronous link converter (SLC) because it takes sinusoidal current at unity power factor from the ac source, both during motoring and braking operations.

Regenerative Braking

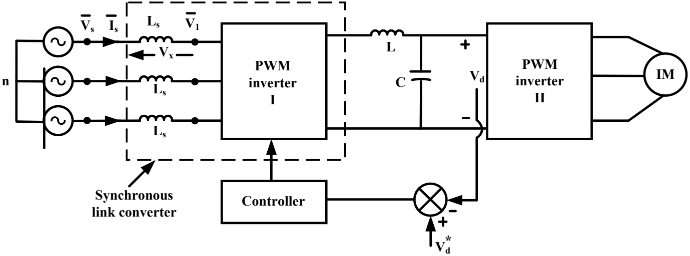


Figure 4. VSI IM drive with regenerative braking capacity (SLC fed PWM inverter IM drive).

- Thus, while its performance is superior, it requires less devices than a dual converter.
- A regenerative drive with a SLC and PWM inverter is shown in Fig. 4.
- The inductors L_s and PWM inverter I constitute a SLC.
- PWM inverter I is operated to produce voltage V_1 of required magnitude and phase with a low harmonic content.
- So that current source I_s is nearly sinusoidal and in phase with V_s for motoring and $180°$ out of phase for braking, thus giving unity power factor.

Regenerative Braking

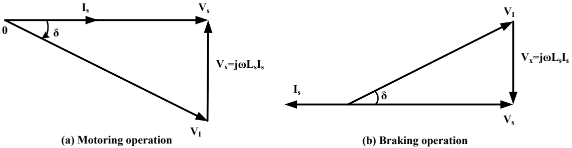


Figure 5. Phasor diagrams of synchronous link converter.

- The phasor diagrams are shown in Fig. 5 (a) and (b).
- For each value of I_s, V_1 of given phase and magnitude is required.
- This can be easily realized in sinusoidal pulse-width modulation (PWM).
- In sinusoidal PWM magnitude and phase of V_1 depends on the magnitude and phase of modulation signal.
- $\therefore V_1$ of given phase and magnitude can be produced by producing modulating signal of required magnitude and phase.
- Since V_1 is produced by PWM inverter, it does not contain low frequency harmonics.
- The inductor L_s filters out high-frequency harmonics to produce a nearly sinusoidal source current I_s.
- The phasor diagrams of Fig. 5 are similar to that of a synchronous machine.
- Thus, the behavior of synchronous link converter is similar to that of a synchronous machine → synchronous link converter.

Regenerative Braking

- When the drive of Fig. 4 is operating in steady state, power supplied (taken) by SLC must be equal to power taken (supplied) by PWM inverter II.
- Since the two work independent of each other, this is achieved by providing closed-loop control of the dc link voltage.
- When the power supplied by SLC to the dc link equals the power taken by PWM inverter II, no energy will be supplied or taken from the capacitor C and its voltage will be constant and equal to the reference value V_d^*.
- If now the load on IM is increased, power taken by PWM inverter II from the dc link will be higher than the power supplied by the SLC.
- Hence, the capacitor voltage V_d will fall below its reference value V_d^*.
- The closed-loop voltage control will increase the value of I_s and, therefore power supplied to the dc link.
- Hence, the dc link voltage will be brought back to the reference value.

Regenerative Braking

- Since SLC works as a boost converter, the closed-loop control of dc link voltage provides the drive with ride through capability against a voltage sag and under voltage.
- When ac source voltage falls, the closed loop voltage control maintains the dc link voltage constant by increasing I_s and thus, the motor continues to be provided constant voltage, and therefore, produces same maximum power and torque.
- The drive of Fig. 2 (b) can have regenerative braking capability by replacing controlled rectifier by a dual converter.
- The SLC cannot be used because it requires operation at a constant dc link voltage, whereas with six step inverter dc link voltage must be varied.
- The drive of Fig 2 (a) will have regenerative braking capability if a two-quadrant chopper of Fig. 5.44 (capable of providing voltage of one polarity and current in either direction) is used.

Four Quadrant Opeartion

- Four quadrant operation can be obtained by any drive with braking (regenerative or dynamic) capability.
- A reduction of the inverter frequency, to make synchronous speed less than the motor speed, transfers the operation from quadrant I (forward motoring) to II (forward braking).
- 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 the switches of any two legs of the inverter.
- This transfers the operation to quadrant III (reverse motoring).
- The inverter frequency and voltage are increased to get the required speed in reverse direction.

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Thank You

Synchronous Motor and and Brushless dc Motor Drives

Lecture-20

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1. Synchronous Motor Variable Speed Drives
2. Variable Frequency Control
3. Self-Controlled Synchronous Motor Drive
4. Permanent Magnet ac Motor Drives

Variable Frequency Control

- $N_s \propto f \rightarrow$ motor speed can be controlled by varying the frequency.
- As in case of an induction motor, constant flux operation below base speed is achieved by operating the motor with a constant (V/f) ratio; which is increased at low speeds to compensate for the stator resistance drop.
- All types of synchronous motors give operation with a constant pull-out torque.
- Rated voltage is reached at the base speed.
- For higher speeds, the machine is operated at a rated terminal voltage and variable frequency, and the pull-out torque decreases with an increase in frequency.

Modes of Variable Frequency Control

- Variable frequency control may employ any of the two modes: (i) true synchronous mode or (ii) self-controlled mode, also known as self-synchronous mode.
- In true synchronous mode, the stator supply frequency 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.
- This allows rotor speed to track the changes in synchronous speed.
- When the desired synchronous speed (or frequency) is reached, the rotor pulls into step, after hunting oscillations.
- Variable frequency control not only allows speed control, but it can also be used for smooth starting and regenerative braking, as long as it is ensured that the changes in frequency are slow enough for the rotor to track changes in synchronous speed.
- A motor with damper winding is used for pull-in to synchronism.

Modes of Variable Frequency Control

- In self-control mode, the stator supply frequency is changed so that synchronous speed is the same as rotor speed.
- This ensures that rotor runs at synchronous speed for all operating points.
- Consequently, rotor cannot pull-out of step and hunting oscillations are eliminated.
- For such applications, the motor may not require a damper winding.
- In self-control mode, the stator supply frequency is changed in proportion to the rotor speed so that the rotating field produced by the stator always moves at the same speed as the rotor (or rotor field).
- Since, the voltage induced in the stator phase has a frequency proportional to rotor speed, self-control can be realized by making the stator supply frequency to track the frequency of induced voltage.
- Alternatively, sensors can be mounted on the stator to track the rotor position. These sensors are called rotor position sensors.
- The frequency of signals generated by these sensors is proportional to rotor speed.
- Hence, the stator supply frequency can be made to track the frequency of these signals.

Variable Frequency Control of Multiple Synchronous Motors

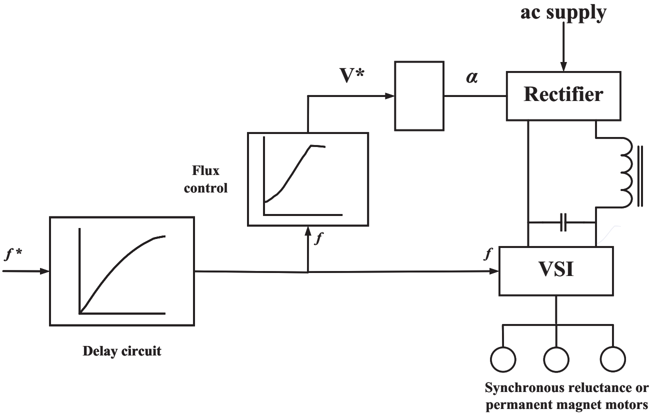

Figure 1. Variable frequency control of multiple synchronous motors.

- A drive operating in true synchronous mode is shown in Fig. 1.
- Frequency command f^* is applied to a voltage source inverter through a delay circuit so that rotor speed is able to track the changes in frequency.
- A flux control block changes stator voltage with frequency to maintain a constant flux below rated speed and a constant terminal voltage above rated speed.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

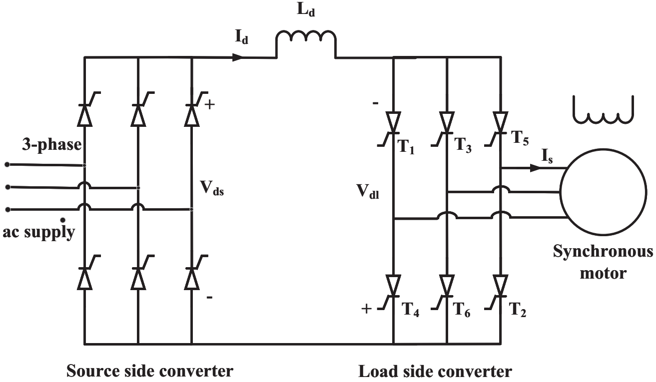

Figure 2. Self-controlled synchronous motor drive employing load commutated inverter.

- A self-controlled synchronous motor drive employing a load commutated thyristor inverter is shown in Fig. 2.
- In large power drives wound field synchronous motor is used.
- Medium power drives employ permanent magnet synchronous motors.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- The drive employs two converters, which are termed here as source side converter and load side converter.
- The source side converter is a 6-pulse line commutated thyristor converter.
- For a firing angle range $0 \leq \alpha_s \leq 90^\circ$ it works as a line-commutated fully controlled rectifier delivering positive V_{ds} and positive V_{ds} and for the range of firing angle $90^\circ \leq \alpha_s \leq 180^\circ$ it works as a line-commutated inverter delivering negative V_{ds} and positive I_d.
- When synchronous motor operates at a leading power factor, thyristors of the load side converter can be commutated by the motor induced voltages in the same way, as thyristors of a line-commutated converter are commutated by line voltages.
- Commutation of thyristors by induced voltages of load (here load is a motor) is known as load commutation.
- Firing angle is measured by comparison of induced voltages in the same way as by the comparison of line voltages in a line commutated converter.
- Converter operates as an inverter producing negative V_{dl} and carrying positive I_d for $90^\circ \leq \alpha_l < 180^\circ$.
- For $0^\circ \leq \alpha_l \leq 90^\circ$ it works as a rectifier giving positive V_{dl}.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- For $0^\circ \leq \alpha_s \leq 90^\circ$, $90^{\leq \alpha_l \leq 180^\circ}$ and with $V_{ds} > V_{dl}$, the source side converter works as a rectifier and load side converter as an inverter, causing power to flow from ac source to the motor motoring operation.
- When firing angles are changed such that $90^\circ \leq \alpha_s \leq 180^\circ$ and $0^\circ \leq \alpha_l \leq 90^\circ$, the load side converter operates as a rectifier and the source side as an inverter.
- Consequently, the power flow reverses and machine operates in regenerative braking.
- The magnitude of torque depends on $(V_{ds} - V_{dl})$.
- Speed can be changed by control of fine side converter firing angles.
- When working as an inverter, the firing angle has to be less than 180° to take care of commutation overlap and turn-off of thyristors.
- It is common to define a commutation lead angle for load side converter as

$$\beta_l = 180^\circ - \alpha_l. \tag{1}$$

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- If commutation overlap is ignored, the input ac current of the converter will lag behind input ac voltage by angle α_L. Since motor input current has an opposite phase to converter input current, the motor current will lead its terminal voltage by an angle β_l.
- $\therefore$ motor operates at a leading power factor.
- Lower the value of β_l, higher the motor power factor and lower the inverter rating.
- The commutation overlap for the load side converter depends on the subtransient inductance of the motor.
- The motor is provided with a damper winding in order to reduce subtransient inductance.
- This allows operation with a substantially lower value of β_l.
- The damper winding does not play its conventional roles of starting the machine as an induction motor and to damp oscillations, because rotor and rotating field speeds are always the same.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- In a simple control scheme, the drive is operaied at a fixed value of commutation lead angle β_{lc} for the load side converter working as an inverter and at $\beta_l = 180^\circ$ (or $\alpha_l = 0^\circ$) when working as a rectifier.
- When good power factor is required to minimize converter rating, the load side converter when working as an inverter is operated with constant margin angle control.
- If commutation overlap of the thyristor under commutation is denoted by u, then the duration for which the thyristor under commutation is subjected to reverse bias after current through it has fallen to zero is given by

$$\gamma = \beta_l - u. \tag{2}$$

- For successful commutation of thyristor

$$\gamma > \omega t_q. \tag{3}$$

Where, t_q is the turn-off time of thyristors and ω is the frequency of motor voltage in rad/s.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- Since $u \propto I_d$, for a given I_d, β_l can be calculated such that the thyristor under commutation is reverse biased for a duration γ_{min} which is just enough for its commutation.
- This in turn minimizes β_l and maximizes motor power factor.
- Since γ is kept constant at its minimum value γ_{min}, the control scheme is called constant margin angle control.
- The dc link inductor L_d reduces the ripple in the dc link current I_d and prevents the two converters from interfering with each other's operation.
- Because of the presence of inductor in the dc link, the load side converter when working as an inverter, behaves essentially as a current source inverter of Fig. **??**, except that thyristor commutation is now performed by motor induced voltages.
- Consequently, the motor phase current has six step waveform of Fig. **??** (b).
- Because of the dc current through L_d, the ac input current of source side converter also has a six step current waveform.
- The dc line current I_d flows through the machine phase for 120° in each half cycle.
- Fundamental component of motor phase current I_s has following relationship with I_d

$$I_s = \frac{\sqrt{6}}{\pi} I_d. \tag{4}$$

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- For machine operation in the self-controlled mode, rotating field speed should be the same as rotor speed.
- This condition is realized by making the frequency of the load side converter output voltage equal to the frequency of voltage induced in the armature.
- Firing pulses are therefore generated either by comparison of motor terminal voltages (as induced voltages are not directly accessible) or by the rotor position sensors.
- Self control is ensured when firing pulses are generated by the comparison of motor terminal voltages (as induced voltages are not directly accessible).
- Alternatively firing pulses are generated by rotor position sensors, which are stationary and suitably aligned with the armature winding.
- The frequency of induced voltages depends on the speed of rotor (or rotor field) and their phase depends on the location of rotor poles with respect to the armature winding.
- Hence, signals generated by rotor position sensors have the same frequency as that of the induced voltages and they have a definite phase with respect to induced voltages.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- Load side converter thyristors are fired in the sequence of their numbers with 60° interval.
- $\therefore$ for the control of load side converter thyristors, in all six rotor angular positions are required to be detected per cycle of the induced voltage.
- The Hall-effect sensors can detect the magnitude and direction of a magnetic field.
- Hence, three Hall-effect sensors can detect the six rotor positions.
- The sensors are mounted at 60° electrical intervals and aligned suitably with armature winding.
- As stated earlier the load side converter and the current source inverter of Fig. **??** perform essentially the same function.
- The only difference between the two is that while the former uses the load commutation, the later uses forced commutation.
- Load commutation has a number of advantages over forced commutation:
  (i) it does not require commutation circuits,
  (ii) frequency of operation can be higher, and
  (iii) it can operate at power levels beyond the capability of forced commutation.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- Load side converter performs somewhat similar function as commutator in a dc machine.
- The load side converter and synchronous motor combination functions similar to a dc machine.
- First, it is fed from a dc supply and secondly like a dc machine the stator and rotor fields remain stationary with respect to each other at all speeds.
- Consequently, the drive consisting of load side converter and the synchronous motor is known as commutator less dc motor.
- At low speeds, motor induced emf will be insufficient to commutate the thyristors of load side converter, therefore, at start and for speeds below 10 % of base speed, the commutation of load side converter thyristors is done by forcing the current through conducting thyristors to zero.
- This is realized by making source side converter work as inverter each time load side converter thyristors are to be turned off.
- For example thyristors T_1 and T_2 are to conduct together for 60° electrical.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- After 60°, source side converter will be made to work as an inverter, which will reverse V_{ds} and turn-off thyristors T_1 and T_2.
- Now the source side converter operation is brought back to rectification and gate pulses are released to T_2 and T_3 to turn them on and make them conduct together for next 60° electrical.
- Since frequency of operation of load side converter at low motor speeds is very low compared to source frequency, such an operation can be realized.
- This operation of the inverter can be termed as pulsed mode.
- This mode of operation requires rotor position sensors.
- $\therefore$ even when the normal operation above 10 % of base speed is implemented by sensing motor terminal voltages, rotor position sensors will be needed to realize pulsed mode.
- The dc supply to the field can be provided from a controlled rectifier through slip-rings and brushes.
- Alternatively, brushless excitation system consisting of diode bridge mounted on the rotor and, therefore rotating with the rotor and supplied by a rotating transformer can be used.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

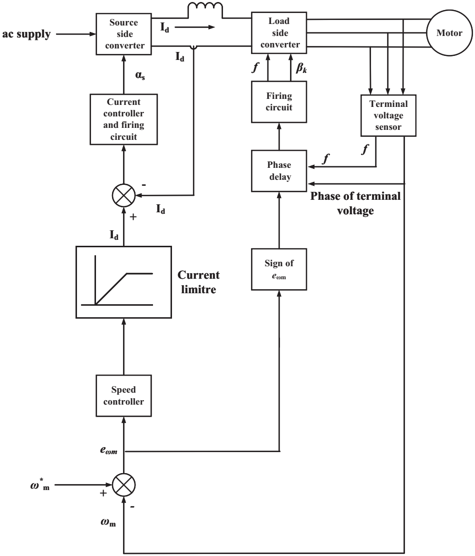

Figure 3. Closed-loop speed control of load-commutated inverter synchronous motor drive.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- The field current is controlled by controlling the input voltage of the transformer by feeding it from an ac voltage regulator.
- The brushless excitation eliminates slip-rings and brushes and associated maintenance.
- A closed-loop speed control scheme is shown in Fig. 3.
- It employs outer speed control loop and inner current control loop with a limiter, like a dc motor.
- The terminal voltage sensor generates reference pulses of the same frequency as the machine-induced voltages.
- The phase delay circuit shifts the reference pulses suitably to obtain control at a constant commutation lead angle β_{lc}.
- Depending on the sine of speed error, β_{lc} is set to provide motoring or braking operation.
- Speed ω_m can be sensed either from the terminal voltage sensor or from a separate tachometer.
- An increase in reference speed $omega_m$ produces a positive speed error.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- β_{lc} value is set for motoring operation.
- The speed controller and current limiter set the dc link current reference at the maximum permissible value.
- The machine accelerates fast. When close to the desired speed, the current limiter desaturates and the drive settles at the desired speed and at the dc link current which balances motor and load torques.
- Similarly a reduction in reference speed produces a negative speed error.
- This sets beta kc for regenerative braking operation (i.e., 180°) and the motor decelerates.
- When speed error changes sign β_{lc} value is set for motoring operation and the drive settles at the desired speed.
- Advantages of this drive → high efficiency, four-quadrant operation with regenerative braking, high power ratings (up to 100 MW) and ability to run at high speeds (6000 rpm).
- Applications → high speed and high power drives for compressors, blower, fans, pumps, conveyers, steel rolling mills, main line traction, ship propulsion and aircraft test facilities.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

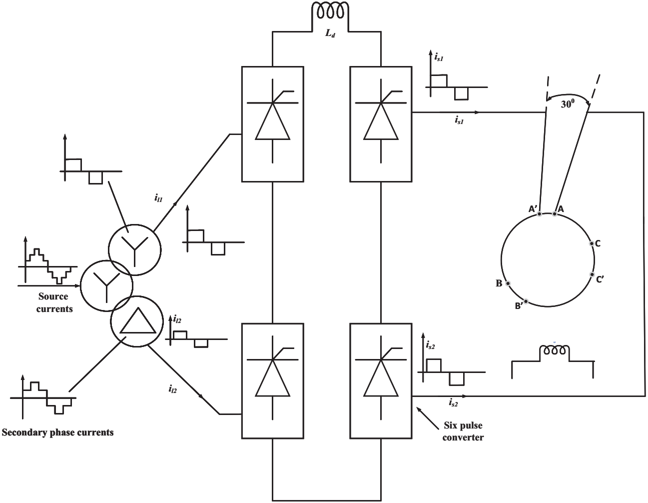

Figure 4. High power synchronous motor drive with series connections of 6-pulse converters to obtain 12-pulse configurations.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- At very high power levels, harmonics generated at the source and motor terminals require special attention.
- Single line diagram of a high power drive is shown in Fig. 4.
- The source side harmonics are reduced by using a 12-pulse converter.
- For this two six-pulse converters are connected in series.
- The supply for the converters is obtained through a transformer with primary connected in star and having two secondary windings, one connected in star feeds one six pulse converter and another connected in delta feeds another six pulse converter.
- This way 30° phase shift is provided between the input voltages of two six-pulse converters.
- The input current waveforms of two converters and source current are shown in Fig. 4.

Self-Controlled Synchronous Motor Drive Employing Load Commutated Thyristor Inverter

- The source current is more close to the sinusoidal compared to six-pulse converter.
- The harmonics in motor current produce torque pulsations and losses in rotor and damper windings due to induced harmonic currents.
- These effects are minimized by using a synchronous motor equipped with two three phase windings on stator with a phase shift of 30° between their axes and feeding them from two series connected six-pulse load commutated converters with their output current phase shifted by 30° (Fig. 4).
- The resultant stator mmf has twelve pulse waveform.
- ∴ torque pulsations and rotor and damper winding losses are reduced.
- When the motor has only single winding, it can be supplied with 12-pulse current by connecting the series connected six-pulse converters with the motor via transformers in the same way as mentioned above for source side converters.

Permanent Magnet ac Motor Drives

- Permanent magnet synchronous motors are now commonly known as permanent magnet ac (PMAC) motors.
- They are classified based on the nature of voltage induced in the stator as sinusoidally excited and trapezoidally excited; in the former induced voltage has a sinusoidal waveform and in the later induced voltage has trapezoidal waveform.
- These PMAC motors are commonly known as sinusoidal PMAC and trapezoidal PMAC motors.
- A sinusoidal PMAC motor has distributed winding (similar to wound field synchronous motor) in the stator.
- It employs rotor geometries such as inset or interior.
- Rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform.
- The stator of a trapezoidal PMAC motor has concentrated windings and a rotor with a wide pole arc.

Permanent Magnet ac Motor Drives

- The voltage induced in the stator phase has a trapezoidal waveform.
- It employs rotor geometries such as surface magnets shown in Fig. 7.1.
- The speed of PMAC motors is controlled by feeding them from variable frequency voltage currents.
- They are operated in self-controlled mode. Rotor position sensors are employed for operation in self-control mode.
- Alternatively, induced voltage can be used to achieve self-control.
- The current trend is to use MOSFET for low voltage and low power applications and IGBT for others.
- In the past, self-controlled variable frequency drives employing a sinusoidal PMAC motor were also called brushless dc motor drives.
- They are now simply called sinusoidal PMAC motor drives.
- The self-controlled variable frequency drives employing a trapezoidal PMAC motor → brushless dc motor drives or trapezoidal PMAC motor drives.

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Thank You

Traction Drives

Lecture-21

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1. Electric Traction Services
2. Nature of Traction Load

Electric Traction Services

Major application of electric drives is in electric traction, i.e., to transport men and material from one place to another.

Electrical traction services can be broadly classified as

- (i) Electric Trains.
- (ii) Electric buses, trams (or tramways) and trolleys.
- (iii) Battery driven and solar powered vehicles.

Electric Trains

- Electric trains run on fixed rails.
- Electric trains are classified → main line trains and suburban trains.

Main-Line Trains

- Intercity passenger and goods trains which come under this category have trailer coaches carrying men and material driven by locomotives carrying driving motors.
- Since driving motors travel with locomotive, power supply to the motors is arranged in two ways:

  (i) from overhead transmission line in electrical locomotive and

  (ii) from diesel generator set mounted on the locomotive in a diesel-electric locomotive.
- In an electric locomotive, the driving motor and power modulators are housed in the locomotive.
- An overhead transmission line is laid along or above the track (or rails).
- A current collector mounted over the locomotive has a conductor strip which slides against the supply conductor and thus maintains continuous contact between the supply and the locomotive.

Main-Line Trains

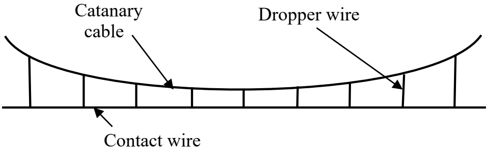


Figure 1. Transmission arrangement (catanary).

- The supply conductor is commonly known as a contact wire.
- To ensure good contact between the current collector and contact wire, the latter is maintained horizontally by supporting it with ‘catanary cable’ and ‘dropper’ wires, which in turn are supported at the interval by appropriate structures (Fig. 1).
- For high-speed trains, contact wires are rarely given a vertical inclination to the track greater than 1 in 300.
- At the same time, the lateral position of the wire above the rails is staggered from side to side between supports to even the wear on the collector, caused as it slides along the contact wire.

Main-Line Trains

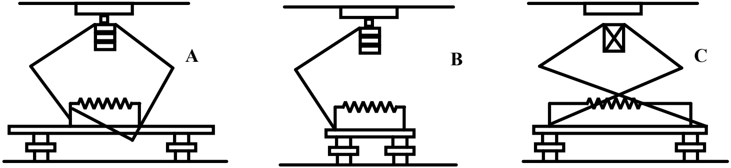


Figure 2. Typical forms of pantograph. A: Open frame; B: Faiveley; C: Crossed arm.

- The commonly used collector has the shape of a pentagon, therefore, it is called a pantograph collector (Fig. 2).
- It has a conducting strip which is pressed against the contact wire by springs.
- The collector strips are usually of steel with grease lubrication, or of carbon, in which case no lubrication is needed.

Main-Line Trains

- Function of the pantograph → to maintain as constant pressure as possible between the collector strip and contact wire and to prevent any vertical oscillation of the collector strip, as these will produce arcing due to breaking of electric contact.
- When the pantograph is not in use, it is maintained in lower position with the help of stiff springs.
- When to be used, the collector strip is raised by compressed air.
- For high-speed trains, the design of collector is critical.
- As supply lines are to be laid all along the track, with adequate spacing, the economy dictates use of minimum number of such lines.
- $\therefore$ single phase supply is used.
- The current enters locomotive through the collector, flows through the primary of a step-down transformer, and returns to supply earth through locomotive wheels and one of the rails on which locomotive travels.
- Thus, avoiding the need for a second conductor.
- Main secondary winding (or windings) of the transformer feeds the power modulator, which in turn powers the driving motors.

Main-Line Trains

- The auxiliary secondary windings of the transformer feed power for other needs of the train such as lighting, fans, airconditioning etc.
- The locomotive power ratings can be as high as 6000 HP and more.
- Powering such a large single-phase load can lead to large unbalance in the supply system which is always three-phase.
- In order to reduce unbalance, the track supply is divided into sections which are electrically isolated from each other, and substations supplying these sections are connected to different phases of the three-phase supply.
- Though the unbalance is reduced, its magnitude still remains large.
- If the three-phase supply system capacity is much larger than the power drawn by the locomotive, then this unbalance will not significantly affect the three-phase supply system.
- Therefore, it is essential that the main source of traction supply should be sufficiently large.
- When locomotive travels through different sections, the supply is momentarily disconnected when it moves from one section to another.

Main-Line Trains

- The movement during the transition occurs because of the inertia. Momentary disruption of power produces inductive voltage spikes.
- Electric traction is classified as single phase ac and dc depending on the supply.
- It has nothing to do with the motor type.
- Based on the study done by French and German Railways in late forties, 25 kV was considered suitable for ac traction.
- Indian Railways have also adopted 25 kV, 50 Hz, single phase supply for ac traction.
- 25 kV, 50 Hz ac supply is now being used for main-line traction throughout India, except Bombay-Igatpuri section where 1500 V dc traction is in use.
- In a diesel-electric locomotive, the electric power is generated within the locomotive by a diesel engine driven electric generator.
- Capital cost of electric traction employing electric locomotive is very high.
- Because of the necessity of expensive transmission lines, the total cost (capital plus running) is lower compared to diesel-electric traction using diesel-electric locomotive.

Suburban Trains

- They are employed for transporting men within a city or between cities located at small distances.
- The main difference being that the distance between consecutive stops (or stations) is much smaller for suburban trains than the main line.
- The suburban trains are also known as local trains. Because of shortage of land in cities, they are often run through underground tunnels and are called subway trains, metros or simply underground trains.
- Suburban trains are driven by motor (or motorized) coaches, instead of locomotives.
- Each motor coach is equipped with an electric drive with its controls in driver's cabin and a pantograph collector.
- Usual pattern is to use motor coaches and trailer coaches in the ratio 1: 2.
- In high speed trains the ratio may be increased to 1: 1. The trains employing motor coaches and trailer coaches are also known as electrical multiple unit (EMU) trains.
- Such an arrangement provides the flexibility in train size. During light traffic periods, one or two units, each consisting of one motor coach and two trailer coaches form a train.

Suburban Trains

- During rush hours. number of such units are coupled together. Each unit is provided with local and remote control equipment, so that all the motor coaches of a train can be controlled from the driver's cabin of the front motor coach.
- The electric supplies for suburban trains are similar to those used in main line trains, except in case of underground trains.
- The cost of making underground tunnels is very large, therefore, their size is kept minimum possible.
- As enough space is not available for a high voltage line, in underground traction, the voltage chosen is usually small, 500 to 1000 V (in Calcutta metro it is 750 V dc).
- Usually, it is dc because first it needs lesser clearance from the supply conductor to the train body and the ground and secondly the power modulator becomes simpler and less expensive.
- The underground trains generally do not use overhead transmission line.
- It is a common practice to use a third rail for the supply.
- The rail may be mounted between the running rails or on one side of the tunnel.
- Brushes are mounted underneath or on the side of the motor coaches, depending on the location of the supply rail, for current collection. The rails are cheaper than overhead supply, so they are preferred whenever the chance of pedestrains comming across them is remote.

Electric buses, Trams and Trolleys

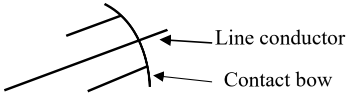


Figure 3. Current collector for an electric bus.

- Because of lower running expenses and complete absence of pollution, electric buses are preferred over diesel engine driven buses for city services and are quite popular in Europe and Canada.
- Their main disadvantage is the need for elaborate supply network, which makes their capital cost very high (though total expenses are lower) and makes them unsuitable for intercity services.
- The electric buses, also known as electric cars, usually consists of single motor driven coach.
- The supply is generally low voltage de overhead line running along the road.
- As the currents are usually small, the collector consists of a rod carrying at its end a grooved wheel or two rods bridged by a contact bow (Fig. 3).

Electric buses, Trams and Trolleys

- Collector system is provided with enough flexibility for the bus to manoeuvre sideways through traffic without adversely affecting contact between the collector and supply conductor.
- Arrangement has also to be provided for an additional conductor for the return of current.
- The trams are electric buses (or cars) which run on rails and consist of a single motor coach In some cases, one or two trailer coaches are added.
- Current collection is similar to buses and its return can be through one of the rails.
- As trams run on rails, their path through roads is fixed.
- Unless roads are very wide, their movements along with the rest of traffic slows down. Hence, they are not employed anymore.
- Electric trolleys used for transporting material in mines and factories mostly run on rails. They are similar to trams, only the shape is different.

1 Electric Traction Services

2 Nature of Traction Load

Nature of Traction Load

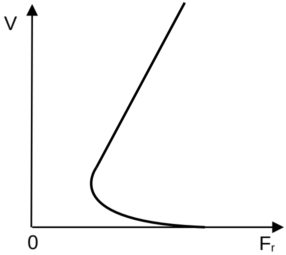


Figure 4. Relation between speed V and train resistance F.

- When the train runs at a constant velocity on level track, a number of frictional forces oppose its motion.
- The friction at bearings, guides, etc., are classified as internal friction.
- The rolling friction between wheels and rails, and friction between wheel-flanges and rails is termed as external friction.
- A third category consists of air friction which is independent of weight of the train but depends upon its size and shape, velocity and relative direction of wind.
- All these frictional forces together are known as train resistance.
- Variation of train resistance (F) with speed (V) is shown in Fig. 4, load torque versus speed curve will have similar nature.

Nature of Traction Load

- The train resistance (or load torque) can also be identified in terms of a common classification of friction such as windage, viscous friction, coulomb friction, and stiction.
- Stiction has a large value and the influence of air friction, which varies as the square of speed, is quite prominent at high speeds.
- When deciding the torque requirements of driving motors, the torque components required to provide acceleration and to overcome gravity must also be considered.
- Owing to large inertia, particularly of electric trains, accelerating torque forms major proportion of the total torque in the accelerating range.
- Because of large values of stiction and accelerating torque, the torque requirement at the start and during acceleration is much higher than the torque needed for running at the highest speed.
- $\therefore$ only those drives which develop large torque from zero to the base speed are suitable for traction application.

Coefficient of Adhesion C_A

- In traction, the task of driving equipment consists of pushing the carriage on which it is mounted and pulling coaches and wagons behind it.
- Wheels coupled to the motors, either directly or through a reduction gear, are known as driving wheels.
- When motors run, driving wheels in their effort for rotation, exert a frictional force on the track tangentially backward at points of contact between the driving wheels and track.
- As a result, driving wheels experience a reaction in the forward direction, consequently, wheels and the carriage move in the forward direction.
- If at the points of contact between the driving wheel and the track, force applied is large, the wheels may slip, then the wheels turn, but carriage remains stationary.
- A very important factor in traction drives, coefficient of adhesion μ_a, provides a quantitative measure of the tendency of wheels to slip and is defined as:

$$\mu_a = \frac{\text{Maximum tractive effort that can be applied without slipping of wheels}}{\text{Weight on the driving axles}} \tag{1}$$

Coefficient of Adhesion C_A

- Weight on the driving axles is also the weight on the driving wheels. It is also known as adhesive weight.
- Tractive effort is the total force at the rims of driving wheels, and therefore, it is proportional to the motor torque.
- Value of the coefficient of adhesion depends on the condition of surfaces of driving wheels and track at the point of contact.
- The coefficient of adhesion is somewhat analogous to the coefficient of friction; while latter depends on conditions at one point of contact, the former depends on conditions at several points of contact.
- Eq. 1 suggests that for a given value of the coefficient of adhesion, there is a maximum value of torque that can be applied without the slipping of driving wheels; this in turn places restriction on the maximum value of acceleration.
- When wheel of a train slips at start, it slides against the same point on the rail.
- Due to friction and heat produced, rail surface is damaged at the point of contact, commonly called ‘burning of track’.

Coefficient of Adhesion C_A

- It further increases the tendency to slip. As a result, the life of the track and wheels is reduced.
- In road vehicles, if wheel slip occurs when vehicle is already in motion, it not only reduces the life of tyres, but can lead to serious accidents as the driver loses complete control of the vehicle.
- That is why every care is taken in all electrical vehicles to avoid wheel slip.

The coefficient of adhesion depends on many factors such as

- (i) Type and condition of surfaces at the point of contact.
- (ii) Vehicle speed.
- (iii) Nature of motor speed-torque characteristic.
- (iv) Motor connections.
- (v) Type of power modulator.

Coefficient of Adhesion C_A

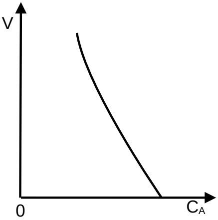


Figure 5. Relation between train speed V and coefficient of adhesion C_A.

- The coefficient of friction, and therefore, the coefficient of adhesion depends on the nature of the material used for making the track and wheels and also on conditions of track and wheel surfaces,
- Example → presence of oil, grease, water, snow and mud reduces the coefficient of adhesion.
- Electric buses possessing rubber tyres rolling on metalled road have much higher coefficient of adhesion than electric trains having steel wheels rolling on steel rails.
- Coefficient of adhesion decreases with increase in speed. The nature of variation is shown in Fig. 5.
- If oil, grease, water, snow and mud fall on the rail or on wheel surface, it will be shifted towards the left.

Coefficient of Adhesion C_A

- It also depends on the nature of speed-torque characteristics of the driving motor and has a higher value for motors with low regulation of speed, i.e., when for a given increase of speed, the drop in torque is large.
- When a wheel slips, the speed of the driving motor increases.
- The torque drops by a large amount in motors with low regulation of speed, and the wheels regain their grip on rails immediately avoiding slip.
- In a locomotive more than one motors are employed.
- They may be connected in suitable series and parallel combinations.
- The ability of the locomotive to cross a section of the track with low adhesive coefficient depends on this combination of series-parallel connection.
- To understand this, let us consider the case of two motors with the option of connecting them either in series or in parallel; the power modulator can always be designed to obtain voltage suitable for any of these connections.
- Due to the bad patch on the track, let the wheels coupled to one motor slip.
- The speed of this motor will increase, decreasing the current and torque.
- When the two motors are connected in series, current and torque of the other motor will also decrease, decreasing the total available torque.

Coefficient of Adhesion C_A

- When connected in parallel, their current and torque are independent.
- Therefore, the current and torque of other motors will not decrease, i.e., the total torque will be higher.
- Thus, according to Eq. 1, for the same condition of track, the coefficient of adhesion will have a higher value for the parallel connection.
- Since the maximum torque that can be applied without wheel slip is higher for parallel connection, there is greater chance for the train to negotiate bad patch on the track without wheel slip.
- When the locomotive has four motors, from the point of view of the coefficient of adhesion, the best connection will be all motors in parallel.
- Next best will be two pairs of series connected motors in parallel and the worst will be all four motors in series.

Coefficient of Adhesion C_A

- A power modulator capable of allowing stepless change in motor voltage is preferable from the point of view of wheel slip.
- If the voltage can only be controlled in steps, then at the time of speed change, motor torque may exceed the value at which wheels slip.
- For example, in 25 kV ac traction using tap changers, the dc motors voltage can be controlled only in discrete steps.
- Whenever changeover is done to increase the speed, the motor voltage increases abruptly, causing a step increase in current and torque.
- Thus, during transition, the instantaneous value of torque is much larger than what would occur if the motor voltage is gradually increased with speed.
- $\therefore$ the tendency for wheel slip is minimized if the power modulator is capable of providing stepless change in voltage.
- Coefficient of adhesion is also affected by the speed of response of the power modulator and drive.
- When a wheel slips, the wheel slip detection circuit gives command for the reduction of motor torque so that the slipping wheel can regain the grip.
- In a drive where the torque can be reduced faster, the tendency for wheel slip will be lower.

Duty Cycle of Traction Drives

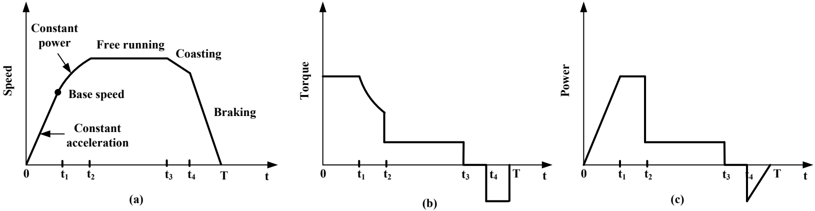


Figure 6. Speed-, torque and power-time curves for an electric train.

- The duty cycle of electric trains is explained with the help of speed-, torque- and power-time diagrams (Fig. 6), which are drawn for travel between two consecutive stations on a levelled track.
- The train is accelerated at the maximum permissible torque, giving constant maximum acceleration.
- The power increases linearly with speed.
- At time t_1, the base speed and the maximum allowable power is reached.
- Further acceleration occurs at constant power.

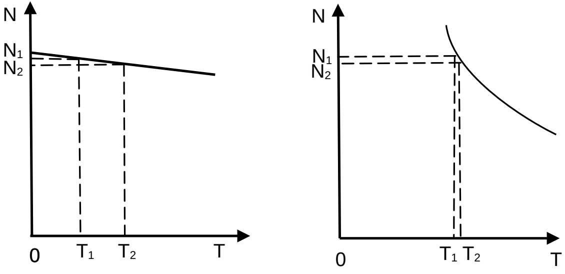
Duty Cycle of Traction Drives

- Torque and acceleration decrease inversely with speed.
- At the time t_2 the drive torque equals the load torque and steady speed is reached.
- The acceleration time (0 to t_2) has two parts: acceleration at a constant torque (0 to t_1 and acceleration at a constant power (t_1 to t_2).
- From t_2 to t_3, train runs at a constant speed and constant drive power.
- This duration is known as free running.
- At t_3, supply to the motor is turned off, reducing the drive torque to zero.
- Now the train coasts due to its own inertia.
- At a suitable time t_4, brake is applied to stop the train at the next station.
- The area beneath the speed-time curve gives the distance covered.
- Thus, larger the area beneath the speed-time curve, greater will be the distance covered in a given time or lesser will be the time taken to cover a given distance.

Duty Cycle of Traction Drives

- The diagrams of Fig. 6 are drawn for a levelled track.
- When gradients are involved, they will be modified. When going up the gradient, the acceleration and free running speed will be low.
- While going down the gradient, braking may be required both during acceleration and free running, and coasting may have to be avoided.
- During braking, the deceleration will be low because a part of braking torque is utilised in balancing the gravitational pull due to the down gradient.
- The duration of various parts of the duty cycle of Fig. 6 will differ according to the distance between two consecutive stations (or stops) and the type of service.
- In case of main line trains all parts-acceleration, free running, coasting and braking, will be usually present, although their duration will change with the distance between consecutive stations.
- In case of suburban trains, the distance between stations can be so small that brakes may have to be applied even before the train is fully accelerated.
- In that case free running and coasting will be absent.
- When the distance is larger than this, either free running or coasting may be present.
- In high-speed trains, coasting is avoided as it reduces the average speed.

Load Sharing between Traction Motors



(a) Separately excited motor

(b) Series motor

Figure 7. Torque sharing between motors.

- An electric locomotive uses more than one motor.
- Each motor drives set of axles and wheels.
- Due to wear and tear, the diameters of wheels become different after they have been in service for quite some time.
- The linear speed of the locomotive and wheels will be the same.
- $\therefore$ motor speeds will be different due to the difference in the diameters of the wheels driven by them.

Load Sharing between Traction Motors

- Consequently, the motors will not share the torque equally.
- Figs. 7 (a) and (b) show the torque sharing for separately excited dc and series dc motors when the locomotive uses two motors, which run at speeds N_1 and N_2 due to the difference in wheel diameters.
- Torque developed by two motors are shown as T_1 and T_2.
- When T_2 becomes equal to the rated motor torque T_r, T_1 is smaller than T_r.
- The total torque that the locomotive can develop without overloading any motor is only $(T_1 + T_r)$, which is less than the sum of rated motor torques $2\,T_r$.
- Thus, unequal torque sharing virtually derates the torque capability of the locomotive.
- The derating is larger for separately excited motor than the series motor.
- In general, torque sharing will be more unequal for motors with low-speed regulation.
- Note that this requirement is contrary to that for adhesive coefficient.
- The adhesive coefficient has a larger value for a motor with low-speed regulation.
- When motors are fed from different converters, equal torque sharing can be achieved by suitably controlling converter output voltages.
- But then the cost of drive goes up as two converters, each of 50 % rating, will be more expensive than a single converter of full rating.

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Thank You

Traction Drives

Lecture-22

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1 Main Line and Suburban Train Configurations

2 Calculations of Traction Drive Rating and Energy Consumption

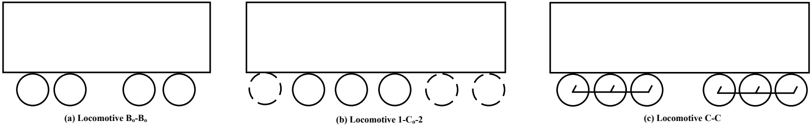
Difference in Constrcution of Main Line and Suburban Trains

- In main line trains, distance between the consecutive stations is generally large.
- Acceleration and deceleration times form only a very small proportion of the total time of travel between the two stations.
- Therefore, average speed mainly depends on the free running speed and acceleration is allowed to be low to suit the passengers' convenience.
- In the main line trains which are driven by locomotives, the maximum weight on driving wheels can be at most equal to the weight of locomotive.
- For a given value of coefficient of adhesion, the torque that can be applied without wheel slip is directly proportional to weight on the driving wheels.
- As the weight on driving wheels is restricted to the weight of locomotive, the main line trains can have only moderate acceleration and deceleration.

Difference in Constrcution of Main Line and Suburban Trains

- In case of suburban trains, as already stated, distance between consecutive stations is usually very small.
- The acceleration and deceleration times form a major proportion of the total travelling time.
- To get a high average speed, it is necessary to reduce acceleration and deceleration times.
- For a given value of coefficient of adhesion, acceleration and deceleration can be increased only by increasing the ratio of the weight on driving wheels and total weight of the train.
- Hence, instead of a locomotive, motorized coaches are used.
- Each coach has its own driving motors.
- The usual pattern is to use the motorized and trailer coaches in the ratio of 1: 2; the ratio is increased up to 1: 1 in case of high speed trains.
- This arrangement allows a much higher proportion of the train weight to come on the driving wheels, compared to a locomotive, and hence, much faster acceleration and deceleration can be obtained.

Driving Axle Code for Locomotives



(a) Locomotive B_o-B_o

(b) Locomotive 1-C_o-2

(c) Locomotive C-C

Figure 1. Arrangement of driving axles and wheels and locomotive code.

- Weight of the locomotive is supported on axles which are coupled to wheels.
- The weight per axle is limited by the strength of the track and bridges, and usually varies between 15 and 30 tons.
- Total number of axles is calculated by the following equation,

$$\text{Number of axles} = \frac{\text{Weight of locomotive}}{\text{Permissible weight per axle}} \tag{1}$$

- Certain amount of torque is needed for driving a given train.

Driving Axle Code for Locomotives

- The number of driving axles and coupled motors are described using a code.
- If a locomotive possesses two driving axles, it belongs to category B.
- Similarly, for a 3-, 4- and 6-axle drive, the symbols used are C, B-B and C-C, respectively.
- If each axle is driven by an individual motor; a subscript ‘o’ is used along with these symbols.
- In case axles are divided into groups and each group is driven by a single motor, only letters B and C are appropriately used.
- The number of dummy (non-driving) axles is denoted by numerals.
- Use of these codes is illustrated in Fig. 1 where dotted circles represent dummy wheels, code B_o-B_o, (Fig. 1 (a)) denotes that the locomotive has four driving axles and each axle is driven by its own driving motor.
- Code 1-C_o-2 in Fig. 1 (b) shows that it has three driving axles each driven by a separate motor, and 3 dummy axles.
- Fig. 1 (c) indicates that the locomotive has 3 + 3 driving axles and a group of three axles is provided with one driving motor.

1 Main Line and Suburban Train Configurations

2 Calculations of Traction Drive Rating and Energy Consumption

Calculations of Traction Drive Rating and Energy Consumption

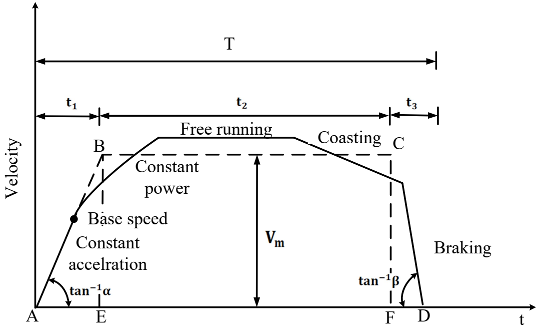


Figure 2. Speed-time curve and its approximation.

- For simplification in calculations, it is approximated by a trapezoidal curve having constant values for acceleration and deceleration.
- As the area beneath curve represents distance covered, the area of the trapezoidal curve is chosen equal to the area of actual curve.
- Let D be the distance in km, T is the time taken by train to move from A to D in s, V_m is the free running speed of trapezoidal curve in km/hr (kmph) and α and β are acceleration and deceleration in km/hr/s (kmphps).

Calculations of Traction Drive Rating and Energy Consumption

- Then V_{av} = Average speed of the train, kmph.

$$V_{av} = \frac{\text{Distnace between the stops, km}}{\text{Actual time of run, hours}} = \frac{3600\, D}{T}. \tag{2}$$

- V_d = Scheduled speed of the train, kmph

$$V_d = \frac{\text{Distance between the stops, km}}{\text{(Actual time of run + Time of stop) hours}} \tag{3}$$

- From the trapezoidal curve,

$$t_1 = \frac{V_m}{\alpha} \text{ s} \quad \text{and} \quad t_2 = \frac{V_m}{\beta} \text{ s}$$

$$\begin{aligned} D = \text{Area of trapezoidal curve} &= \frac{V_m}{3600}\left(\frac{1}{2}t_1 + t_2 + \frac{1}{2}t_3\right) \\ &= \frac{V_m}{7200}\left[2T - (t_1 + t_3)\right] \\ &= \frac{V_m}{7200}\left[2T - \left(\frac{V_m}{\alpha} + \frac{V_m}{\beta}\right)\right] \text{ km.} \end{aligned} \tag{4}$$

- Eq. 4 has five variables D, V_m, T, α, β. If any four values are known, the fifth can be evaluated.

Tractive Effort and Drive Ratings

- Tractive effort is the force developed at the rims of driving wheels for moving trains.
- In main line trains it is caused by locomotive and in suburban by motor coaches.
- Draw bar pull is the force exerted by a locomotive through draw bar for a moving train.
- Thus, draw bar pull is less than the tractive effort by the force required to move the locomotive.
- The tractive effort has to perform the following functions.

  (i) Accelerate the train mass horizontally.

  (ii) Accelerate the rotating parts of train such as wheels, gears, axles and the rotor of the motor.

  (iii) Overcome force due to gravity when moving up-gradient.

  (iv) Overcome train resistance.

Tractive Effort

- (i) **Tractive effort required to accelerate the train mass horizontally** (in newtons) at an acceleration of α kmphps is given as

$$F_{al} = (1000\,M) \times \frac{\alpha \times 1000}{3600} = 277.8\,M\,\alpha, \quad \text{N.} \tag{5}$$

  Where, M is the mass in tonnes.

- (ii) **Tractive effort required to accelerate the rotating parts:** Rotating parts consists of wheels, axles, gears and rotor of the motor.
- The inertia of gears and axles can be ignored in comparison to that of wheels.
- Moment of inertia of wheels

$$J_1 = 2\,N_x\,J_w. \tag{6}$$

  Where, J_w is the moment of inertia of one wheel in kg-m^2 and N_x is the number of axles on the train.

- Let N = number of driving motors
  n_1 = teeth on motor gear wheel
  n_2 = teeth on axle gear wheel
  R = radius of the wheel, m
  J_m = moment of inertia of one motor, kg-m^2.

$$a = \frac{a_1}{a_2} = \frac{\text{wheel speed}}{\text{motor speed.}} \tag{7}$$

- Then the moment of inertia of motors referred to wheels

$$J_2 = \frac{N J_m}{a^2} \tag{8}$$

$$\text{Acceleration (in m/s}^2\text{)} = \frac{\alpha \times 1000}{3600}, \text{mpsps.}$$

$$\text{Acceleration (in rad/s}^2\text{)} = \frac{\alpha \times 1000}{3600\,R}, \text{rpsps.}$$

Tractive Effort

- Tractive effort for driving rotating parts

$$F_{a2} = (J_1 + J_2)\,\frac{\alpha \times 1000}{3600\,R} = \left(2\,N_x\,J_w + \frac{N\,J_m}{\alpha^2}\right)\frac{\alpha}{3.6\,R^2}. \tag{9}$$

- Total tractive effort required for accelerating the train on a level track (in newtons)

$$F_a = F_{a1} + F_{a2} = 277.8\,M\,\alpha + \left(2\,N_x\,J_w + \frac{N\,J_m}{\alpha^2}\right)\frac{\alpha}{3.6\,R^2} \tag{10}$$

$$= 277.8\,M_e\,\alpha,\ \text{N}. \tag{11}$$

Where, M_e is defined as the effective mass of the train.

It accounts for rotating parts in addition to he train mass.

It is around $8 - 15\,\%$ higher than M.

Eq. 11 can also be written as

$$F_a = \frac{277.8}{9.81}\,M_e\,\alpha = 28.3\,M_e\,\alpha,\ \text{kg}. \tag{12}$$

Tractive Effort

- (iii) **Tractive effort required to overcome force due to gravity:** When moving up-gradient, the drive has to produce tractive effort to overcome force due to gravity.
- When deciding drive rating, gradient with the maximum permissible slope is to be considered.
- In railway practice, gradient is expressed as rise in meters in track distance of 1000 m and denoted by G.
- Now, tractive effort required to overcome force due to gravity will be

$$\begin{aligned} F_g &= 1000\,M \times \frac{G}{1000} \times g, \quad \text{N} \\ &= 9.81\,M\,G, \quad \text{N} \qquad (13) \\ &= M\,G, \quad \text{kg.} \qquad (14) \end{aligned}$$

Tractive Effort

- (iv) **Tractive effort required to overcome train resistance:** Variation of train resistance with speed is shown in Fig. It is not possible to accurately represent it analytically.
- Among several empirical relations proposed, the simplest is based on the understanding that train resistance is due to various kinds of frictions.
- ∴ it will have three basic components: due to (a) coulomb friction which is independent of speed, (b)viscous friction which is proportional to speed, (c) air friction which is proportional to speed squared.

$$F_t = A + B\,V + C\,V^2, \quad \text{N.} \tag{15}$$

Where, V is the speed of the train, and A, B, C are constants.

- Eq. 15 suggests that it is difficult to estimate the train resistance.
- Since it is quite small compared to F_a, an approximate value od F_r can be used and is often assumed as r newtons per tonne weight of the train. Thus,

$$F_r = r\,M, \quad \text{N} \tag{16}$$

$$= \frac{r\,M}{9.81}, \quad \text{kg.} \tag{17}$$

- For calculating drive rating, r is chosen to be 20 N/tonne.

Tractive Effort

- (v) **Total tractive effort required to move the train:**

$$\begin{aligned} F_t &= F_a + F_g + F_r \\ &= 28.3\, M_e\, \alpha \pm M\, G + \frac{M\, r}{9.81}, \quad \text{kg} \qquad (18) \\ &= 27..8\, M_a\, \alpha \pm 9.81\, M\, G + M\, r, \quad \text{N.} \qquad (19) \end{aligned}$$

  +ve sign → train movement up-gradient and −ve → down the gradient.
- (vi) **Motor torque rating:** The total torque at the rims of driving wheels is

$$\begin{aligned} &= \text{Total tractive effort (in newtons)} \times R \\ &= R\, F_t, \quad \text{N-m.} \qquad (20) \end{aligned}$$

  Where, R is the radius of the driving wheels in meters.
- Total torque referred to the motor shaft is

$$T_t = \frac{a\, R\, F_t}{\eta_t}, \quad \text{N-m.} \qquad (21)$$

  Where, η_t is the efficiency of transmission.
- Torque per motor is given as

$$T_m = \frac{a\, R\, F_t}{\eta_1\, N}, \quad \text{N-m.} \qquad (22)$$

  Where, N is the number of motors.

Specific Energy Consupmtion

- An estimate of energy required to operate train is needed so that running expenses can be calculated.
- To facilitate these calculations the term specific energy consumption has been defined as the energy consumed in watt-hours per tonne of train weight and per kilometer of distance travelled.
- The energy output at the driving axles is pent to:
  (i) Accelerate the train.
  (ii) Overcome the gradient.
  (iii) Overcome the train resistance.
- **(i) Energy output at the driving axles to accelerate the train (E_a):** Assuming trapezoidal speed-time curve of Fig. 2.

$$E_a = F_a \text{in newtons} \times \text{Distance travelled during acceleration (AE) in meters}$$

$$= F_a \times \text{Area of triangle ABE}$$

$$= 277.8\, M_e\, \alpha \left(\frac{1}{2}\, \frac{V_m \times 1000}{3600}\, \frac{V_m}{\alpha} \right) \times \frac{1}{3600} = 0.01072\, V_m^2\, M_e, \quad \text{Wh.} \quad (23)$$

Specific Energy Consupmtion

- **(ii) Energy output at the driving axles to overcome the gradient (E_g):**

$$E_g = F_g \text{ in newtons} \times D_1 \times 1000. \qquad (24)$$

Where, D_1 is the distance in km for which the power remains on.

- From the trapezoidal curve, this distance is AF which is equal to the area $ABCF$. Thus,

$$E_g = \frac{9.81\, M\, G \times 1000\, D_1}{3600}, \quad \text{Wh}$$

$$= 2.725\, M\, G\, D_1, \quad \text{Wh}. \qquad (25)$$

$$\text{Distance } D_1 = D - \text{Distance } FD$$

$$= D - \left[\frac{1}{2}\,\frac{V_m}{3600} \times \frac{V_m}{\beta}\right], \quad \text{km}. \qquad (26)$$

- **(iii) Energy output at the driving axles to overcome the train resistance (E_r):**

$$E_r = F_r \text{ in newtons} \times D_1 \times 1000, \quad \text{Ws}$$

$$= \frac{1000\, r\, M\, D_1}{3600} == 0.2778\, r\, M\, D_1, \quad \text{Wh}. \qquad (27)$$

Specific Energy Consupmtion

- Total energy output at the driving axles (E_t)

$$E_t = E_a + E_g + E_r$$
$$= 0.01072\, V_m^2\, M_e \pm 2.725\, M\, G\, D_1 + 0.2778\, r\, M\, D_1, \quad \text{Wh.} \tag{28}$$

- Specific energy output in Wh per tonne per km = $\frac{E_t}{M\,D}$, Whptpkm.

$$= \frac{0.01072\, V_m^2}{D}\,\frac{M_e}{M} \pm 2.725\, G\,\frac{D_1}{D} + 0.2778\, r\,\frac{D_1}{D}, \quad \text{Whptpkm.} \tag{29}$$

- Specific energy consumption is given as

$$E_0 = \frac{\text{Specific energy output}}{\eta}. \tag{30}$$

Where, η is the efficiency of transmission and motor.

- When regenerative braking is used, energy regenerated is fed back to the source, thus reducing specific energy consumption.

Specific Energy Consupmtion

- The energy output at the driving axle E_b as follows:

$$E_b = -0.01072\, V_b^2\, M_e \pm 2.725\, M\, G\, (D - D_1) + 0.2778\, M\, r\, (D\ D_1), \quad \text{Wh.} \tag{31}$$

Where, V_b is the initial speed during braking, + ve sign is for uo-gradient and – ve for down gradient (for second term on right side only).

- Assuming transmission system and motor efficiency to be the same during motoring and braking

$$\text{Energy consumption} = \frac{E_t}{\eta} - \eta\, E_b. \tag{32}$$

- Specific energy consumption

$$E_0' = \frac{(E_t/\eta) - \eta\, E_b}{M\, D} \tag{33}$$

$$= E_0 - \frac{\eta\, E_b}{M\, D}. \tag{34}$$

- **Maximum Allowable Tractive Effort**
- The maximum tractive effort that can be applied without wheel slip

$$F_m = 9.81\, \mu\, (1000\, M_d) = 9810\, \mu\, M_d, \quad \text{N.} \tag{35}$$

Where, μ is the coefficient of adhesion and M_d is the adhesive weight or weight on the driving wheels.

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Thank You

Traction Drives

Lecture-23

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1 Traction Motors

Motors Employed in Traction

- Earlier, dc series motor was widely used in traction.
- It has high starting torque and capability for high torque overloads.
- With an increase in torque, the flux also increases → therefore for the same increase in torque, the increase in motor current is less compared to other motors.
- Thus, during heavy torque overloads, power overload on the source and thermal overloading of the motor is kept limited to reasonable values.
- The motor speed-torque characteristic is also suitable for better sharing of loads between motors.
- Further, due to a large inductance in the field, sharp fluctuations in supply voltage do not produce sharp peaks in armature current.
- Thus, the motor commutation remains satisfactory, which does not happen in a separately excited motor unless an additional inductance is connected in the armature circuit.

Motors Employed in Traction

- With the availability of semiconductor converters, a separately excited motor is now preferred over the series motor.
- With independent control of armature and field, the speed-torque characteristic of a separately excited motor can be shaped to satisfy the traction requirements in the optimum manner.
- Further, because of the low regulation of its speed-torque characteristics, the coefficient of adhesion has higher value.
- Series motor has a number of limitations.
- The field of a series motor cannot be easily controlled by semiconductor switches.
- If field control is not employed, the series motor must be designed with its speed equal to the highest desired speed of the drive.
- The higher base speeds are obtained using fewer field winding turns.
- However, this reduces the torque per ampere at the start and, therefore, acceleration.

Motors Employed in Traction

- Further, there are a number of problems with regenerative and dynamic brakings of a series motor.
- On the other hand, regenerative and dynamic brakings of a separately excited motor are fairly simple and efficient, and can be carried out down to very low speeds.
- Currently, compound motor is being preferred for traction applications as it incorporate the advantages of both series and separately excited motors.
- Due to the availability of reliable variable frequency semiconductor inverters, squirrel-cage induction motor,s and synchronous motors are now finding applications in traction.
- Because of a number of advantages associated with these motors, they are likely to replace dc motors for traction applications.

Motors Employed in Traction

- Advantages of squirrel-cage induction motors over dc motors → ruggedness, lower maintenance, better reliability, lower cost, weight, volume and inertia, higher efficiency, and ability to operate satisfactorily with sharp supply voltage fluctuations and in dirty environment.
- Drawback of dc motor → the presence of commutator and brushes, which require frequent maintenance, particularly when the flashovers at the commutator occur due to sharp voltage fluctuations.
- In terms of advantages mentioned for squirrel-cage motor in comparison with dc motors, the synchronous motor lies in-between the two and has one important advantage over the squirrel-cage induction motor, that it can be operated at the leading power factor.
- Thus, permitting the use of load-commutated thyristor inverter which is cheaper and occupies less volume and weight compared to forced commutated thyristor inverter required by induction motors.
- The weight and volume of an induction motor drive can also be kept low by using GTO (gate turn-off thyristor) inverter, but is more expensive than a load-commutated thyristor inverter.

Traction Motor Control

- Operation of a dc separately excited motor for traction applications can be divided into three regions.
- First two are identical, i.e. constant torque and power regions.
- In constant torque region, from zero to base speed, the field current is maintained constant at the rated value and the armature voltage is controlled.
- In constant power region, which is carried out above base speed, the armature voltage is maintained constant at the rated value and field current is controlled.
- In both these regions, the armature current is allowed to reach rated value on a continuous basis.
- The limit of constant power operation is reached when a decrease in field current to increase motor speed leads to sparking at the brushes at the rated armature current.
- The motor is said to reach the commutation limit. Operation at higher speeds (and lower field currents) can now be carried out by progressively decreasing the maximum allowable armature current.
- This is the third region of operation in which the available output power of the motor progressively decreases with the increase in speed.

Traction Motor Control

- Traction motor can be operated in third region because the torque required at high speeds is much less compared to the accelerating torque.
- The form of third region is determined by whether or not the motor is compensated and the type of power modulator. For a non-compensated motor, the ratio of maximum allowable armature current to field current is maintained constant.
- In a compensated motor, the maximum allowable armature current is varied inversely with speed.
- A compensated machine is always preferred because it allows greater degree of field weakening and therefore, higher maximum speed.
- The variable frequency controlled squirrel-cage induction motors are also operated in three identical regions.
- Constant torque region from standstill to base speed with a constant V/f ratio and a constant maximum allowable stator current; constant power region from base speed to the speed at which breakdown torque limit is reached, here V and maximum allowable stator current are constant.
- For higher speeds the motor operates in the third region where maximum allowable current is reduced inversely with speed, thus ensuring that the motor torque does not exceed its breakdown value.

Conventinonal dc and ac Traction Drives

The dc Traction Drives Employing Resistance Control:

- The following dc traction drives employing resistance control were in use in India:
- (i) 1500 V dc traction on Bombay-Igatpuri-Pune section for main line and Bombay suburban service.
- (ii) 750 V dc traction in underground trains at Calcutta.
- (iii) 550 V dc traction in Calcutta tramways.
- Each motor coach of 1500 and 750 V dc tractions have four dc series motors with voltage ratings of 750 and 375 V, respectively; two motor are permanently connected in series.
- Similar connection is used in locomotives for 1500 V main line dc traction.
- The 550 V dc traction of Calcutta tramways use two do series motors each rated 550 V.
- Basic control scheme for all these drives is essentially the same.
- When four motors are used, two motors are permanently connected in series to form one pair.
- Thus, the drive will have two pairs each having two motors permanently connected in series.

The dc Traction Drives Employing Resistance Control

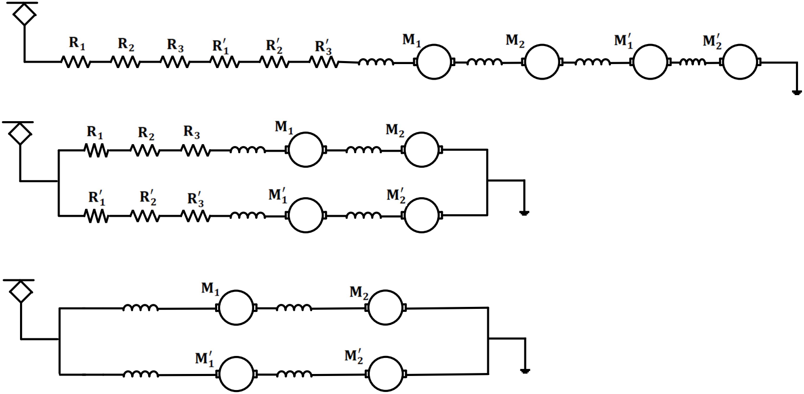

Figure 1. dc Series motor traction drive with resistance control: (a) control from zero to half of base speed; (b) control from half to full of hase speed and (c) operation at base speed.

The dc Traction Drives Employing Resistance Control

- Starting, speed control and torque control up to base speed is carried out with the help of contactor-controlled sectionalised resistors.
- At start both motor-pairs are connected in series with the sectionalised resistors in series as shown in Fig. 1 (a).
- As the train accelerates resistor-sections are cut out one by one so as to limit the starting current within prescribed maximum and minimum limits.
- When all sections of resistance controller are cut out, the motor speed will be nearly half of the base speed.
- For further acceleration, the two motor pairs are connected in parallel with the sectionalised resistor in series with each of them (Fig. 1 (b)).
- The resistor-sections are now cut out, one by one to limit the current within prescribed maximum and minimum limits.

The dc Traction Drives Employing Resistance Control

- When all resistor sections are cut out (Fig. 1 (c)), motors will be running around the base speed.
- Speeds higher than base speeds are obtained by field control. For changing the field current, diverter resistors are connected in parallel with field windings.
- Different steps of control for a motor coach with two motors is obtained when each pair in Fig. 1 is replaced by one motor.
- During transition from series to parallel connection closed circuit transition has to be applied, because it is not desirable to break such a high current.
- Further, the sudden change of current at the time of opening and reconnection will produce step change in torque, causing discomfort to passengers and increasing tendency for wheel slip.
- To avoid this, closed circuit transition is used.

The dc Traction Drives Employing Resistance Control

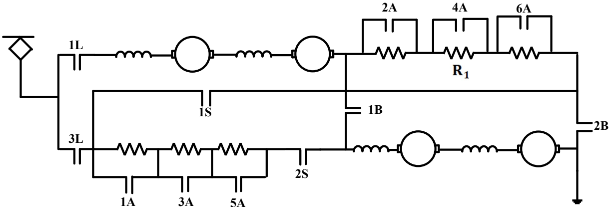

Figure 2. Resistance control of dc traction drive with bridge transition.

- Fig. 2 shows the closed circuit transition using what is known as bridge circuit transition.
- Different steps of control are: (i) close IL, IS and 2S, which connects both motor pairs 1 and 2 in series with sectionalized resistors RI and R2;
  (ii) close progressively 1A to 6A, now motor speeds are nearly half of base speed;
  (iii) close 1B;
  (iv) open IS and IA to 6A;
  (v) close 21. and 2B;
  (vi) open IB, this connects two motor pairs with a sectionalized resistance in series with each, in parallel; without opening motors armature and field circuits.
  (vi) close contacts IA-2A, 3A-4A and SA-6A in pairs successively.
- This connects two motor pairs in parallel and starting process is completed.

The dc Traction Drives Employing Resistance Control

- For dynamic braking, the supply is switched off, fields are reversed and sectionalised resistors are connected across each motor pair.
- The motors work as self-excited generators.
- As the train decelerates, resistor's sections are cut out one by one to maintain good braking torque.
- As the braking ceases at a finite speed, mechanical brakes are applied to stop the train During dynarnic braking, larger resistance is required than during starting.
- Therefore, additional sectionalised resistor is employed along with starting resistor.
- Dynamic braking is not always used.
- For example, in India while underground trains in Calcutta use dynamic braking but not the trains of 1500 V dc traction in Bombay.
- The torque control during motoring and braking is realised by changing the value of armature circuit resistance.
- Additional features are incorporated for smooth acceleration of the train.
- The first few steps during starting are chosen such that the current, and therefore, torque is build up in small steps to avoid any jerk.

The dc Traction Drives Employing Resistance Control

- These steps may be implemented based on the values of dI/dt, whereas later steps are based on the value of I.
- As a number of operations are involved, it will be very tiring for the driver to carry them out manually.
- Automatic controls using contactors and servo drives are used to simplify the job of the driver.
- The above dc traction schemes have several disadvantages. Prominent among these are:
- (i) Low efficiency due to resistance control.
- (ii) Poor adhesion due to: (a) step change in torque and (b) more drooping speed-torque curves because of resistance control.
- (iii) Frequent maintenance due to large number of moving contacts.
- (iv) Unless very large sections are used in the starting and braking resistances, average accelerating and decelerating torques are substantially lower compared to the maximum torque the motors can produce.
- This slows down the average speed of a suburban train.

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer

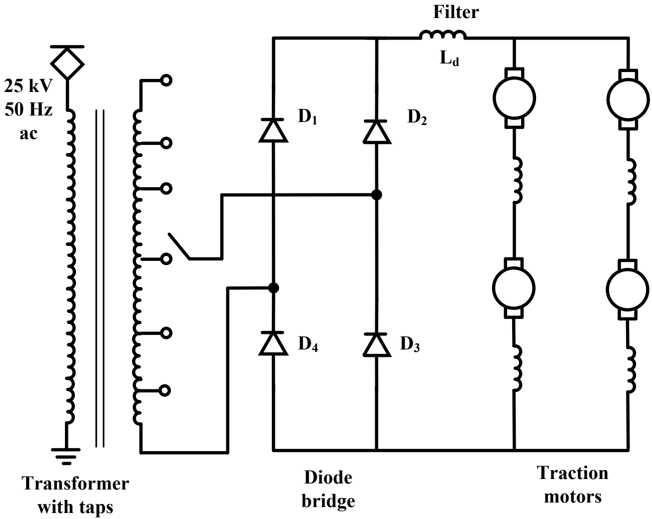

Figure 3. 25 kV, 50 Hz ac traction using transformer with tap changer.

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer

- A step-down transformer reduces the voltage from 25 kV to a suitable value.
- The secondary winding is provided with tappings.
- An on-load tape changer is used to vary the taps on transformer without volatge surges.
- A diode rectifier bridge converts ac to dc and through smoothing reactor L_d feeds dc series traction motors, which are connected in appropriate series-parallel combinations.
- Usually a locomotive with four motors will have series-parallel connection as shown in Fig. 3.
- The tendency for wheel slip will be lowest when all motors are connected in parallel, but then the transformer secondary current rating will be the highest.
- On the other hand, the transformer current rating will be the lowest and the tendency for wheel slip will be highest when all four motors are connected in series.
- The connection of Fig. 3 provides a compromise between the two contradictory requirements.

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer

- The smoothing reactor L_d may be divided into four sections, one in series with each traction motor, so that in the event of a motor fault, a high impedance is in the circuit and motor protection is simplified.
- For starting, and speed and torque control up to base speed, the motor terminal voltage is varied by changing taps on the transformer.
- The speed control above base speed is obtained by connecting a diverter resistor in parallel with the field of each motor.
- Braking is generally provided by mechanical brakes. Dynamic braking has also been used.
- For this, motors have been connected as separately excited generators.
- Fixed braking resistors are connected across the armatures of each motor.
- The fields of all motors are connected in series across an auxiliary dc generator driven by an auxiliary induction motor.
- The current through the motor fields is controlled by controlling the field current of the auxiliary dc generator.

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer

- As the motor decelerates under braking, the motor field current is increased to maintain a specified current through the motor armature.
- The tap-changer may have 20 to 40 taps. Varying them manually can be very tiring for the driver.
- Therefore, the tap changer control has to be automatic. Contactors and servo drives are used to realize automatic control of the tap-changer.

It has the following advantages over dc drives employing resistance control:

- (i) Higher efficiency as the starting, speed and torque control are done by varying armature voltage instead of armature resistance.
- (ii) Better adhesion because with armature voltage control, the motor speed-torque characteristics are less drooping compared to armature resistance control.
- (iii) In underground trains, one is forced to use low voltage due to limited space available between the train and the tunnel.
- No such restriction is applicable to over-ground traction.
- In the case of dc traction, the maximum transmission voltage depends on the number of motors in series and their voltage rating because no simple means were available for stepping down the dc voltage.

The 25 kV, 50 Hz ac Traction Using On-Load Transformer Tap Changer

- As the dc motor voltage rating because of commutator is restricted to 750 V dc and since two motors are permanently connected in series, the dc transmission voltage is chosen as 1500 V.
- In ac transmission, as the voltage can be stepped down easily and efficiently by a transformer, it is possible to use 25 kV voltage for transmission.
- Because of the much higher transmission voltage, the cost of transmission and power loss in transmission is much lower in 25 kV ac traction than in 1500 V dc traction.
- Because of high cost, 1500 V de traction is not used in the new installation.
- Although because of the prohibitive cost of replacement it continues to be there wherever it was installed prior to the development of 25 kV ac traction.

The 25 kV ac traction using transformer with tap changer has following limitations:

- (i) Due to a larger number of moving contacts and parts, the tap changer requires frequent maintenance and is susceptible to frequent failures and fire hazards.
- (ii) As the motor voltage is controlled in steps, adhesion is poor and maximum accelerating torque is lower than with stepless control using semiconductor converters.

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Thank You

Traction Drives

Lecture-24

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1 25 KV ac Traction using Semiconductor Converter Controlled dc Motors

2 Ployphase ac Motors for Traction Drives

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

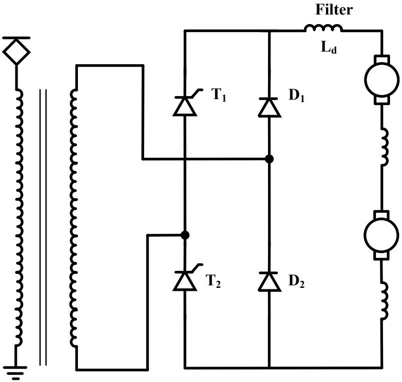

Figure 1. Drive of a shunting locomotive of 25 kV, ac traction with thyristor converter.

- The simplest arrangement consists of a half-controlled converter feeding dc series traction motors is shown in Fig. 1.
- Such an arrangement used in low power shunting locomotives.
- Limitations → (i) at low output voltages the converter power factor is low.
  (ii) the source current with square wave shape is rich in harmonics.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- The rapid changes at the leading and trailing edges of the source current cause sharp harmonic disturbances in the supply network and telecommunication lines.
- The frequency range of harmonics is determined by the steepness of these edges, and their amplitudes by the magnitude of the step.
- Because of the low power rating of a shunting locomotive, the poor power factor, harmonics and harmonic disturbances have only marginal effect on the supply network and telecommunication lines.
- Therefore, such a simple arrangement (Fig. 1) is found acceptable.
- In case of suburban and main line trains power rating is large, consequently the adverse effects of the poor power factor, harmonics and harmonic disturbances on the supply network and telecommunication lines are unacceptable.
- To overcome these limitations, multistage converters, which are operated with sequence control, are used to feed the armatures of traction motors.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

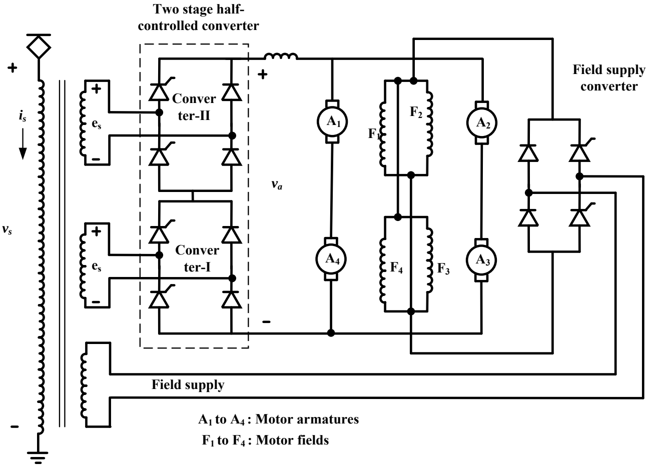

Figure 2. 25 kV ac traction employing two-stage converter feeding four separately excited motors. Field supply is from a single-stage converter.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- Two forms of two-stage converters are shown in Figs. 2 and 4.
- The two-stage converter of Fig. 2 uses two half-controlled converters connected in series.
- A transformer with two identical secondaries feeds the half-controlled converters.
- For dc output voltage from 0 to half, only converter I is controlled and converter II is bypassed by its diodes.
- Fig. 3 (a) shows the waveforms of dc output voltage and the source current for the converter I firing angle $\alpha_1 = 90^\circ$.
- At half of full-output voltage, $\alpha_1 = 0^\circ$.
- For the output voltage between half and full, α_I is retained at 0° and the firing angle of converted II is controlled between 180 and 0°.
- Fig. 3 (b) shows the converter output voltage and source current waveforms for $\alpha_I = 0$ and $\alpha_{II} = 90^\circ$.
- The jump in source current is now reduced to half compared to the single stage converter of Fig. 1.
- Considerable reduction in reactive power, leading to improvement in power factor is obtained.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

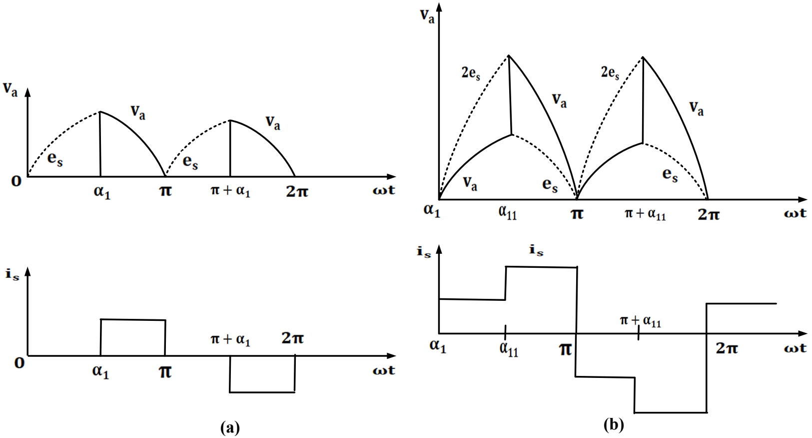

Figure 3. The two-stage converter waveforms at (a) 0.25 and (b) 0.75 per unit output voltages.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- A comparison of reactive power at rated motor current is shown in Fig. 5 for single-stage and two-stage control.
- Field supply, as shown in Fig. 2, is obtained from single-stage half-controlled converter.
- The operation, waveforms and performance of the converter of Fig. 4 are identical to the converter of Fig. 2.
- The series circuit of Fig. 2 requires devices which will withstand half the circuit voltage, but then it requires a transformer with two secondary windings.
- The converter of Fig. 4 requires only a single center-tapped secondary winding, but the devices have to withstand full circuit voltage.
- In main line traction several pairs of two series connected motors are employed (Fig. 2), consequently the converter output voltage falls in the range of 1000 to 1500 V dc.
- The converter of Fig. 2 is found to be more economical for this application.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

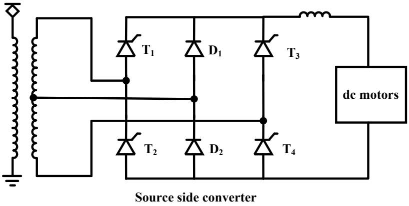

Figure 4. Alternative two stage converter circuit. (field connections are not shown)

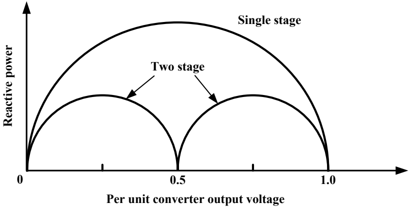

Figure 5. Reactive power at rated motor current for single and two-stage converters.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- In some EMU (suburban) applications all motors are connected in parallel.
- Therefore, the converter output voltage is in the range of 500 to 750 V dc.
- The converter of Fig. 4 is found to be more economical for this application. This is for two stage converters.
- Performance can be improved further by increasing the converter stages beyond two.
- Converters up to four stages have been reported. However, the benefits gained in adding each stage diminishes as the number of stages is increased beyond two.
- In practice, the use of more than two stages becomes uneconomical because of the proportionate increase in the number of devices and transformer secondaries.
- In Fig. 2, four separately excited motors are shown. The number of motors depends on ratings and they are connected in different combinations depending on application and manufacturer's preferences.
- EMUs (electrical multiple units) in Madras suburban trains employ four series motors connected in two parallel pairs with each pair having two series connected motors.
- A 4000 HP locomotive designed by BHEL uses six series motors connected to form three parallel pairs with each pair having two motors in series.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- For EMU (suburban trains) converters, which are relatively low power rating (around 1500 KVA), it has been found that the simple two stage converter of Fig. 2 requires no additional steps to reduce harmonics and improve power factor.
- However, this is not the case with the more powerful converters required for locomotives.
- For locomotives, harmonic filter is connected at the input terminals of each converter to reduce harmonics, both low frequency and high frequency, to prevent interference with telecommunication lines and track circuit and to reduce harmonic disturbance in the supply network.
- Thyristor switched capacitors with two stages are employed to ensure that the power factor does not fall below 0.8.
- Such a scheme has been used in Hitachi Locomotive.
- Recent trend has been to use gate turn-off thyristors (GTOs) instead of thyristors and to operate the converter with an appropriate pulsewidth modulation technique.
- This operation allows the converter operation at unity fundamental power factor throughout and simplifies the harmonic filter design but reduces efficiency.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- In order to obtain smooth acceleration and good adhesion, both in locomotives and EMUs, the converter is operated with closed-loop current control.
- A master controller sets the current reference which is compared with the actual converter output current.
- The error is used to adjust the converter firing angles so that the actual current is maintained equal to the reference current throughout the accelerating range.
- An additional loop may be provided for limiting maximum acceleration.
- This avoids jerks and consequent inconvenience to the passengers.
- As the torque during acceleration is controlled steplessly, high acceleration and good adhesion are obtained.
- Wheel-slip control may be easily incorporated here by having provision for master controller to set the current reference to zero whenever the wheel-slip is detected.
- Because of flexible control many other features can be easily incorporated such as complete automatic control and fault detection.
- Programmable logic controllers, microprocessors or microcomputers can be utilized for this purpose.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- Dynamic braking can be incorporated in both separately excited and series excited motors.
- In case of separately excited motors, fixed resistors are connected across the armature and converter is disconnected.
- The braking torque is controlled by controlling the field current. Controlling the field current is not a problem because fields are in any case fed from controlled rectifiers.
- For dynamic braking, series motors are also connected for separate excitation.
- Field windings connected in series are fed from one of the converters and the converter is supplied by another step-down transformer with low output voltage, because of the low resistance of field windings.
- Fixed resistors are connected across the armature. Braking torque is controlled by controlling the field current.
- Braking performance with field current control and fixed resistors across armatures is inferior compared to control with full field and switched (or sectionalised) resistors across the armature.

25 KV ac Traction using Semiconductor Converter Controlled dc Motors

- Theoretically regenerative braking can be used by replacing half controlled converters of Fig. 2 by fully controlled converters.
- But it is generally not used because of two problems:
- (a) A thyristor converter uses line voltage for commutation. The commutation failure can occur during braking due to following:

  (i) loss of supply,

  (ii) pantograph contact bounce or

  (iii) while passing through neutral sections.

  Then thyristors conduct continuously giving a short circuit both on ac and dc terminals. This problem is overcome when thyristors are replaced by GTOs (gate turn-off thyristors).
- (b) Cost of the locomotive and transmission equipment increases, because with regenerative braking their voltage ratings go up by 10 to 15 %.

1 25 KV ac Traction using Semiconductor Converter Controlled dc Motors

2 Ployphase ac Motors for Traction Drives

Ployphase ac Motors for Traction Drives

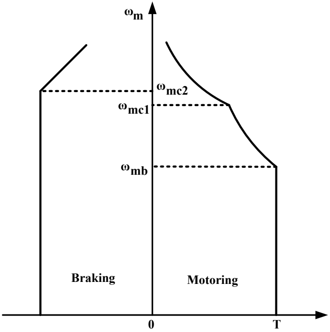

Figure 6. Modes of operation of ac motors with variable frequency control.

- Advantages of ac motors over dc motors → less maintenance, ruggedness and higher power per unit weight or volume.
- Hence, the squirrel-cage induction motor is ideally suitable for traction applications.
- The synchronous motor has also been employed in the traction drives because of the higher η, simpler and low-cost inverter compared to an induction motor.
- Variable frequency control is used both for induction motor and synchronous motor.

- Fig. 6 shows the modes of operation employed for variable frequency control of an induction motor.
- From zero to the base speed ω_{mb}, the motor is accelerated at a constant torque, by keeping the V/f ratio constant and increasing it at low speeds.
- Above the base speed, the motor accelerates in the constant power mode with a constant V and variable f. At a critical speed ω_{mc1} motor's break-down-torque limit is reached.
- $\therefore$ motor power is gradually reduced by operating it with lesser and lesser stator current.
- The figure also shows modes of motor operation during braking.
- From zero to a speed ω_{mc2} motor is braked at a constant torque.
- Above ω_{mc2}, the motor is braked at a decreasing braking torque so as to avoid exceeding wheel to rail adhesion capability and to limit the peak power requirements of the drive.
- Similar curves are obtained in the case of synchronous motor.

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Thank You

Traction Drives

Lecture-25

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1 The dc Traction employing Polyphase ac Motors

2 The ac Traction employing Polyphase ac Motors

The dc Traction employing Polyphase ac Motors

For 1500 V and 750 V dc tractions, following ac drives are widely used.

- (i) Pulsewidth Modulated (PWM) Voltage Source Inverter (VSI) Squirrel-cage Induction Motor Drives.
- (ii) Load Commutated Inverter (LCI) Synchronous Motor Drives.

PWM Voltage Source Inverter (VSI) Induction Motor Drives

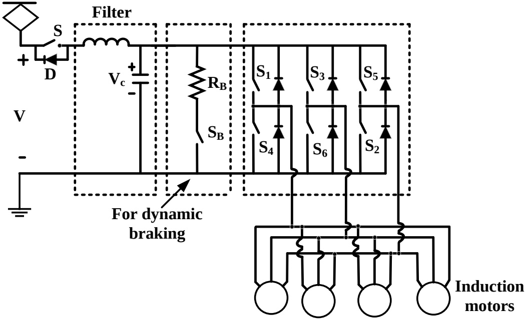

Figure 1. PWM VSI induction motor drive.

- PWM VSI induction motor drive for traction is shown in Fig. 1.
- A pulsewidth modulated voltage source inverter converts dc into variable frequency and variable voltage ac, which is then fed to induction motors.
- Each motor coach of a suburban train may employ a single inverter feeding several squirrel-cage motors connected in parallel.
- The inverter switches S_1 to S_6 may consist of self-commutated devices such as GTO, power transistor or IGBT or a forced commutated thyristor.
- IGBT is the most suitable device for motor coaches.

PWM Voltage Source Inverter (VSI) Induction Motor Drives

- A locomotive, because of high power rating will employ a suitable number of voltage source inverters, with each inverter feeding a suitable number of squirrel-cage motors connected in parallel.
- GTOs are popular, although forced commutated thyristors have also been used in the past.
- Because of PWM inverter, the drive has smooth acceleration.
- The regenerative braking is inherent in the sense that no additional equipment is required to achieve it.
- If the inverter frequency is lowered to make synchronous speed less than the motor speed, the drive operation shifts from motoring to regenerative braking.
- Whenever a possibility exists that regenerated energy may not be fully absorbed by the source, a facility for dynamic braking is added by the incorporation of R_A, S_B, S and D.
- While regenerating, if the source is not able to absorb all the regenerated energy, excess energy is absorbed by filter capacitor C and its voltage V_c rises.
- When V_c crosses a prescribed limit, S is opened to isolate the source from dc link of the inverter and S_B is closed to initiate dynamic braking.

PWM Voltage Source Inverter (VSI) Induction Motor Drives

The PWM VSI induction motor drive has the following advantages,

- (i) Smooth acceleration due to the absence of low-speed torque pulsations.
- (ii) Good adhesion due to fast dynamic response and absence of torque pulsations.
- (iii) Voltage source inverter is more suitable for multi-motor drives.
- (iv) Low weight, volume and cost.
- (v) Simpler control and efficient operation.
- (vi) Regenerative braking capability.

Drawbacks of this drive are

- The possibility of a shoot-through fault in the voltage source inverter.
- The inverter is designed carefully to prevent such a fault.
- Further, expensive fuses are used to protect the switches S_1 to S_6 against a shoot-through fault.

Load Commutated Inverter Fed Synchronous Motor Drives

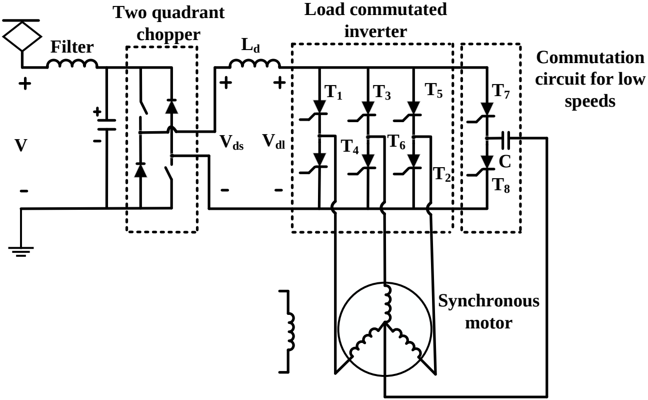

Figure 2. Load commutated inverter synchronous motor drive.

Load Commutated Inverter Fed Synchronous Motor Drives

- The inverter is a current source inverter employing thyristors T_1-T_6.
- The commutation of the inverter thyristor is done by the voltages induced in the armature of the synchronous motor.
- A chopper is used to obtain a variable dc voltage V_{ds} from the fixed source voltage V.
- The V_{ds} is varied with V_{dl} so that a required current is supplied to the dc link, and therefore, to the motor.
- During motoring, the power flows from the dc mains through the chopper, dc link and inverter to the motor.
- When the inverter firing angle is changed from close to 180° to 0°, the voltage V_{dl} reverses.
- If chopper operation is also changed to make V_{ds} negative but less than V_{dl} in magnitude, the power flows from the load through the machine, inverter and chopper to the dc mains, giving regenerative braking operation.
- Here, the arrangement for dynamic braking is not shown, but it can be incorporated in the same way as shown in Fig. 1.

Load Commutated Inverter Fed Synchronous Motor Drives

- Armature induced voltages are too small to commutate inverter thyristors at low speeds, including standstill.
- Thyristors T_7 and T_8 and capacitor C are used to commutate inverter thyristors at low speeds.
- Around 10 % of the base speed gate pulses are withdrawn from T_7 and T_8 and the load commutation is employed.
- Due to the presence of L_d inverter is essentially current source inverter.
- $\therefore$ each traction motor is fed by its own inverter.
- Four such inverters will be required if there are four traction motors.
- Further, because of current source characteristics, the inverters can be connected in series but not in parallel.
- Thus, when four traction motors are used one alternative will be to connect all four inverters in series fed by a common chopper.
- Such a series connection will have an adverse effect on adhesion.
- Alternatively, one can connect two inverters in series, and each such series pair is then fed by its own chopper.

Load Commutated Inverter Fed Synchronous Motor Drives

This drive has the following features in comparison to PWM VSI induction motor drive:

- (i) Because of an additional power stage (i.e., chopper), the converter efficiency is lower, but the motor efficiency is higher
- (ii) Due to the presence of large inductance L_d, the drive has a slow dynamic response giving inferior adhesion.
- Larger weight and volume.
- Each motor should have its own inverter and these inverters can be connected in series but not in parallel.
- When large traction motors are involved the drive becomes expensive and complex. The series connection also has an adverse effect on adhesion.
- Inverter is more reliable due to the absence of shoot-through fault.
- Because of torque pulsations produced by harmonics, the acceleration is not smooth. This also has an adverse effect on adhesion.

The ac Traction employing Polyphase ac Motors

Following ac drives are widely used in 25 kV traction,

- (i) Current Source Inverter (CSI) Squirrel-Cage Induction Motor Drive.
- (ii) PWM Voltage Source Inverter (VSI) Squirrel-Cage Induction Motor Drive.
- (iii) Load Commutated Inverter (LCI) Synchronous Motor Drive.

CSI Squirrel-Cage Induction Motor Drive

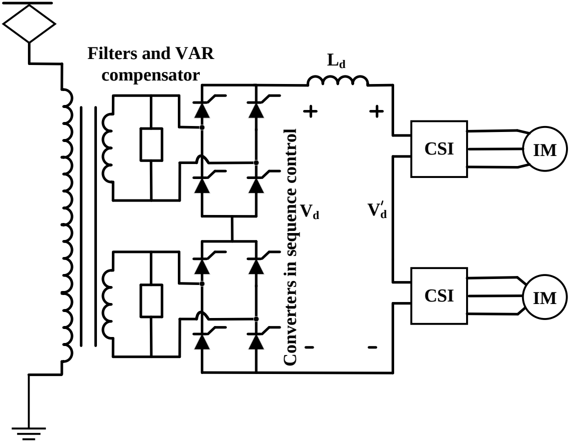

Figure 3. CSI squirrel-cage induction motor drive.

CSI Squirrel-Cage Induction Motor Drive

- Fig. 3 shows the CSI squirrel-cage IM traction drive details.
- In a multistage converter ac is converted into dc with sequence control to improve the converter power factor and to reduce the harmonics produced by it.
- Filters and static VAR compensators are used to maintain a power factor above 0.8 and to keep the harmonics within acceptable limits.
- Current source inverter (CSI) converts dc into variable frequency current, which is then fed to the induction motor.
- Each motor is fed from a separate CSI.
- Since CSI are not suitable for parallel operation, they are connected in series.
- When four motors are employed, one alternative will be to connect all four inverters in series, each feeding its own motor.
- A single converter in sequence control then feeds all four inverters.

CSI Squirrel-Cage Induction Motor Drive

- Another alternative will be to connect two inverters in series powered by one sequence-controlled converter (Fig. 3).
- Two such pairs, each consisting of two inverters fed from one sequence-controlled converter, are then supplied from a common transformer.
- At low speeds, pulse width modulation is sometimes employed to achieve a smooth start.
- Regenerative braking capability is inherent in the drive.
- For this, inverter frequency is reduced to shift motor operation from motoring to braking and the converter is operated as inverter.

Features of the drive

- (i) Bulky, heavy and expensive.
- (ii) Poor adhesion due to slow dynamic response and series connection.

PWM VSI Squirrel-Cage Induction Motor Drive

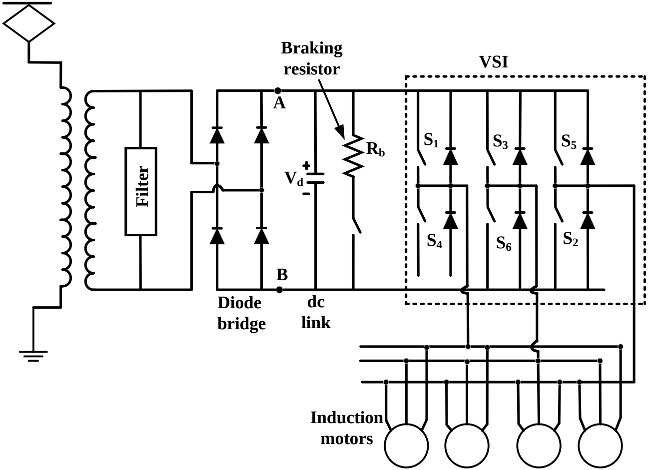

Figure 4. PWM VSI squirrel cage IM drive with dynamic braking.

PWM VSI Squirrel-Cage Induction Motor Drive

- The PWM VSI squirrel-cage motor tractions drive is shown in Fig. 4.
- dc link is supplied from ac source through a transformer and a diode rectifier.
- Because of the use of diode rectifier, regenerative braking is not possible, hence, dynamic braking is employed.
- Operation of the drive is the same as that of the drive of Fig. 1 except that regenerative braking is not possible.
- Circuit of Fig. 5 is a 1-phase SLC, and therefore, employs 1-phase PWM inverter.
- The inverter and inductor L_s, together form SLC.
- For producing a given value of I_s, in phase with V_s, the PWM inverter produces an ac input voltage V_1 of given phase and magnitude, as shown in phasor diagrams of Fig. 5 (b) and (c) for motoring and regenerative braking operations, respectively.
- During motoring operation, power flows from the source through SLC, dc link and inverter into the motor.
- Here I_s is in phase with V_S and V_d and I_d have polarities as shown in the Fig. 5.

PWM VSI Squirrel-Cage Induction Motor Drive

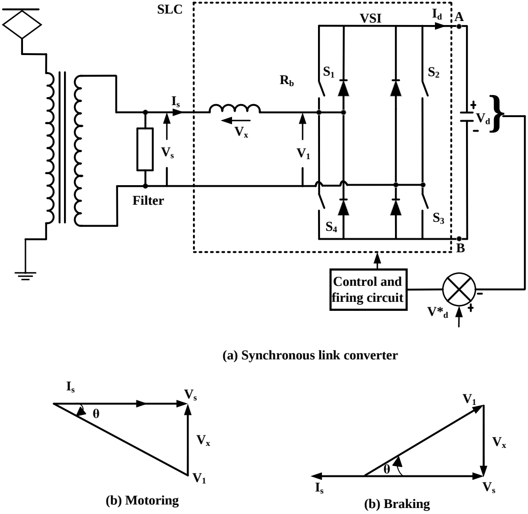

Figure 5. SLC operation at unity power factor for motoring and regenerative braking operation.

PWM VSI Squirrel-Cage Induction Motor Drive

- When machine operation is shifted to braking, I_d reverses and I_s has a phase of 180° with respect to V_s.
- $\therefore$ power generated by motor flows through inverter, dc link and SLC to ac supply, giving regenerative braking.
- As the power supplied to the dc link is independent of power taken from it, a closed loop control of dc link voltage is used to balance the two (Fig. 5 (a)).
- A constant voltage across the dc link capacitor is obtained when the power supplied to the dc link equals the power taken from it.
- Since the SLC works as a boost converter, the closed-loop control of dc link voltage ensures that the torque and power capability of the drive remain unaffected by a drop in source voltage.
- This SLC fed PWM VSI induction motor drive is the most widely used drive.
- ABB locomotive in Indian Railway has this drive.
- As compared to other ac motor drives employed in ac traction, it has the unique advantages of high power factor, low harmonics in source current achieved with a simple filter and ride-through capability against voltage sag and under voltages.

Load Commutated Inverter (LCI) Synchronous Motor Drive

- Features of the drive → high η, high-speed capability, and the ability for regenerative braking.
- A traction drive is obtained when in Fig. 3 CSI are replaced by LCI and induction motor by synchronous motor.
- LCI has the circuit shown in Fig. 2.
- As compared to the regenerative drive, this drive has a lower power factor and high harmonic content unless heavy filtering and power factor correction are employed.
- French Railways TGV use this drive.

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Thank You

Numerical Problems on Dynamics of Electrical Drives

Tutorial-1

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Numerical Problem-1

A motor drives two loads. One has rotational motion. It is coupled to the motor through a reduction gear with $a = 1$ and an efficiency of 90 %. The load has a moment of inertia of 10 $kg - m^2$ and a torque of 10 $N - m$. Other load has translational motion and consists of 1000 kg weight to be lifted up at a uniform speed of 1.5 m/s. Coupling between this load and the motor has an efficiency of 85 %. Motor has an inertia of 0.2 $kg - m^2$ and runs at a constant speed of 1420 pm. Determine equivalent inertia referred to the motor shaft and power developed by the motor.

Solution-1

- The moment of inertia referred to the motor shaft is given as

$$J = J_0 + a_1^2 J_1 + M_1 \left(\frac{v_1}{\omega_m}\right)^2. \tag{1}$$

- Here, $J_0 = 0.2\,kg - m^2$, $a_1 = 0.1$, $J_1 = 10\,kg - m^2$, $v = 1.5\,m/s$ and $\omega_m = (1420 \times \pi)/30 = 148.7\,rad/s$.

- From Eq. 1 gives,

$$J = 0.2 + (0.1)^2 \times 10 + 1000 \left(\frac{1.5}{148.7}\right)^2 = 0.4\,kg - m^2. \tag{2}$$

- We know that,

$$T_l = \frac{a_1\,Tl1}{\eta_1} + \frac{F_1}{\eta_1^{'}} \left(\frac{v_1}{\omega_m}\right). \tag{3}$$

Solution-1

- Here, $\eta_{1=0.9}$, $a_1 = 0.1$, $T_{l1} = 10\,N-m$, $\eta_1^{'} = 0.85$, $F_1 = 1000 \times 9.81\,N$, $v_1 = 1.5\,m/s$ and $\omega_m = 148.7\,rad/s$.
- Substituting the parameters in Eq. 3,

$$T_l = \frac{0.1 \times 10}{0.9} + \frac{1000 \times 9.81}{0.85}\left(\frac{1.5}{148.7}\right) = 117.53\,N-m. \tag{4}$$

Numerical Problem-2

The drive has following parameters:

$J = 10\,kg - m^2$, $T = 100 - 0.1\,N$, N-m, Passive load torque $T_l = 0.05\,N$, N-m, Where N is the speed in rpm.

Initially the drive is operating in steady-state. Now, it is to be reversed. For this motor characteristic changed to $T = -100 - 0.1\,N$, N-m. Calculate the time of reversal.

Solution-2

- For steady-state speed, $T - T_l = 0$.

$$100 - 0.1\,N - 0.05\,N = 0. \tag{5}$$

$$N = -666.7\,rpm. \tag{6}$$

- When reversing, from Eq. $T = T_l + J\,\frac{d\,\omega_m}{dt}$.

$$J\,\frac{d\omega_m}{dt} = -100 - 0.1\,N - 0.05\,N \tag{7}$$

$$J\,\frac{dN}{dt} = \frac{30}{J\,\pi}\,(-100 - 0.1\,N - 0.05\,N) = -95.49 - 0.143\,N \tag{8}$$

$$t = \int dt = \int_{N_1}^{N_2} \frac{dN}{95.49 - 0.143\,N}. \tag{9}$$

Where, $N_1 = 666.7$ rpm and $N_2 = 0.95 \times -0.666.7 = -633.4\,rpm.$

- Integrating Eq. 9 yields $t = 25.58\,s$.

Numerical Problem-3

A motor equipped with a flywheel is to supply a load torque of 1000 N-m for 10 s, 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 motor has an inertia of 10 $kg - m^2$. Its no load speed is 500 rpm, and the slip at a torque of 500 N-m is 5 %. Assume the speed-torque characteristic of the motor to be a straight line in the region of interest.

Solution-3

- We know that

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \left[\frac{t_h}{log\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \right]. \tag{10}$$

- Here, the no-load is given as

$$\omega_{m0} = \frac{500 \times 2\pi}{60} = 52.4\, rad/s. \tag{11}$$

- Speed at 500 N-m is given as

$$\omega_{mr} = (1 - 0.05) = 52.36 = 49.7\, rad/s. \tag{12}$$

- Now,

$$\frac{T_r}{(\omega_{m0} - \omega_{mr})} = \frac{500}{(52.4 - 49.7)} = 190.8. \tag{13}$$

Solution-3

- Substituting $T_{lh} = 1000\,N-m$, $T_{max} = 700\,N-m$, $T_{min} = T_{ll} = 200\,N-m$, $t_h = 10\,s$ in Eq. 10,

$$J = 190.84\left[\frac{10}{log\left(\frac{1000-200}{1000-700}\right)}\right] = 1871.8\,kg-m^2. \tag{14}$$

- Moment of inertia of the fly wheel is $17871.8 - 10 = 1861.8\,kg-m^2$.

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Thank You

Numerical Problems on Selection of Motor Power Rating

Tutorial-2

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1 Numerical Problems

Numerical Problem-1

A motor operates on a periodic duty cycle in which it is clutched to its load for 10 min. and declutched to run on no-load for 20 min. The minimum temperature rise is 40° C. Heating and cooling time constants are equal and have a value of 60 min. When load is declutched continuously the temperature rise is 15° C. Determine

(i) maximum temperature during the duty cycle, and

(ii) temperature when the load is clutched continuously.

Solution-1

- Since the motor is subjected to a periodic intermittent load, temperature at the end of cycle will be the same as the beginning of cycle. We know that

$$\theta = \theta_{ss}\left(1 - e^{-t/\tau}\right) + \theta_1 e^{-t/\tau}. \quad (1)$$

$$\theta_2 = \theta_{ss}\left(1 - e^{-10/60}\right) + 40\, e^{-10/60} \quad (2)$$

$$\theta_2 = 0.1535\,\theta_{ss} + 33.86. \quad (3)$$

- (i) From Eq. $\theta = \theta'_{ss}\left(1 - e^{-t/\tau\prime}\right) + \theta_2 e^{-t/\tau'}$.

$$40 = 15\left(1 - e^{-20/60}\right) + \theta_2\, \theta^{-20/60}, \quad (4)$$

which gives, $\theta_2 = 49.9^\circ$ C.

- (ii) Substituting value of θ_2 in Eq. 3 gives

$$\theta_{ss} = 104.5^\circ\, C. \quad (5)$$

Numerical Problem-2

A rolling mill driven by a thyristor converter-fed dC motor operates on a speed-reversing duty cycle. Motor field current is maintained constant at the rated value. The moment of inertia referred to the motor shaft is 10,000 kg-m^2. Duty cycle consists of the following intervals:

(i) Rolling at full speed (200 rpm) and at a constant torque of 25,000 N-m for 10 s.

(ii) No load operation for 1 s at full speed.

(iii) Speed reversal from 200 to -200 rpm in 5 s.

(iv) No load operation for 1 s at full speed.

(v) Rolling at full speed and at a torque of 20,000 N-m for 15 s.

(vi) No load operation at full speed for 1 s.

(vii) Speed reversal from -200 to 200 rpm in 5 s.

(viii) No load operation at full speed for 1 s.

Determine the torque and power ratings of the motor.

Solution-2

- Since in a dc motor, at constant field current $T \propto I_a$, torque rating can be evaluated by determining the rms value of torque.

$$\text{Torque during reversal} = J\frac{d\omega}{dt} \tag{6}$$

$$= 10000\,\frac{[200 - (-200)] \times (2\pi/60)}{5} = 83776\,\text{N-m.}$$

$$T_{rms} = \sqrt{\frac{25000^2 \times 10 + (83776^2 \times 5)\,2 + 20000^2 \times 15}{39}} = 47686\,\text{N-m.} \tag{7}$$

- Maximum torque 83776 N-m is only 1.76 times T_{rms}.
- If motor rating is chosen to be 47686 N-m, the maximum current will be only 1.76 times the rated current.
- In a dc motor twice the rated current can always be allowed during transient operation.
- ∴ motor can be rated equal to T_{rms}. Thus, motor torque rating is given as

$$T_{rated} = 47686\,\text{N-m.} \tag{8}$$

$$\text{Power rating} = 47686 \times \frac{200}{60} \times 2\pi = 998.7\,\text{kW.} \tag{9}$$

Numerical Problem-3

A constant speed drive has the following duty cycle:

(i) Load rising from 0 to 400 kW : 5 min.

(ii) Uniform load of 500 kW : 5 min.

(iii) Regenerative power of 400 kW returned to the supply : 4 min.

(iv) Remains idel for : 2 min.

Estimate power rating of the motor. Assume losses to be proportional to $(\text{power})^2$.

Solution-3

- Rated power = rms value of power P_{rms}.
- Now, the rms value of power in the given interval of 5 min.

$$P_1 = \sqrt{\frac{1}{5}\int_0^5 \left(\frac{400}{5}\right)^2 dx} = \frac{400}{\sqrt{3}}\,\text{kW}. \tag{10}$$

$$P_{rms} = \sqrt{\frac{\left(\frac{400}{\sqrt{2}}\right)^2 \times 5 + 500^2 \times +400^2 \times 4}{16}} = 367\,\text{kW}. \tag{11}$$

- Since $P_{max} = 500$ kW is less than two times P_{rms}, motor rating = 367 kW.

Numerical Problem-4

A motor has a heating time constant of 60 minutes and cooling time constant of 90 min. When run continuously on full load of 20 kW, the final temperature rise is $40^\circ C$.

(i) What load motor can deliver 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 10 min followed by 10 min shut down, what is the maximum value of load it can supply during the on load period?

Solution-4

- As the constant and copper losses are not available separately, they are assumed $\propto$ (power)^2, and therefore α is assumed to be zero.
- (i) When $\alpha = 0$, from Eq. 12, the overloading factor is

$$K = \sqrt{\frac{1 + \alpha}{1 - e^{-t_r/\tau}} - \alpha} \tag{12}$$

$$K = \sqrt{\frac{1}{1 - e^{-t_r/\tau}}} = \sqrt{\frac{1}{1 - e^{-10/60}}} = 2.55. \tag{13}$$

- Permitted load = $2.55 \times 20 = 51$ kW. (ii) From Eq. 14 for $\alpha = 0$.

$$K = \sqrt{(\alpha + 1)\frac{1 - e^{-l(t_r/\tau_r)+(t_s/\tau_s)}}{1 - e^{(-t_r/\tau_r)}} - \alpha} \tag{14}$$

$$K = \sqrt{\frac{1 - e^{-\left(\frac{10}{60} + \frac{10}{90}\right)}}{1 - e^{-10/60}}} = \sqrt{\frac{0.2425}{0.1535}} = 1.257. \tag{15}$$

- Permitted load = $1.257 \times 20 = 25.14$ kW.

Numerical Problem-5

Half hour rating of a motor is 100 kW. Heating time constant is 80 min and the maximum efficiency occurs at 70 % full load. Determine the continuous rating of the motor.

Solution-5

- Let P kW be the continuous rating of motor and p_c the constant loss.
- Then at 0.7P, copper loass = constant loss p_c.

$$\text{At P copper loss} = \left(\frac{P}{0.7P}\right)^2 p_c = \frac{p_c}{0.49} \tag{16}$$

$$\alpha = \frac{p_c}{p_{cu}} = \frac{p_c}{p_c/0.49} = 0.49. \tag{17}$$

- Substituting in Eq. 12,

$$K = \sqrt{\frac{1 + 0.49}{1 - e^{-30/80}} - 0.49} = 2.0676. \tag{18}$$

- $\therefore$ the continuous rating = $\frac{100}{2.0676} = 48.37$ kW.

Numerical Problem-6

A thyristor converter-fed dc motor has the following specifications: Rated armature current = 500 A, armature resistance =0.01 Ω. The drive operates on the following duty cycle:

(i) Acceleration at twice the rated armature current for 10 s.

(ii) Running at full load for 10 s.

(iii) Deceleration at twice the rated armature current for 10 s.

(iv) Idling intervall.

The core loss is constant at 1 kW. If β has a value of 0.5, determine the maximum frequency of drive operation.

Solution-6

- Here,

$$E_s = 10\left[(500 \times 2)^2 \times +1000\right] = 110\,\text{kWs}.$$

$$p_{1s}\,t_r = \left[(500)^2 \times 0.01 + 1000\right] \times = 35\,\text{kWs}.$$

$$p_{1r} = 500^2 \times 0.01 + 1000 = 3.5\,\text{kW}.$$

$$\gamma = \frac{1+\beta}{2} = \frac{1+0.5}{2} = 0.75.$$

- Substituting in Eq. 19

$$E_s + p_{1s}\,t_r + E_b = p_{1r}\,(\gamma\,t_{st} + t_r + \gamma\,t_b + \beta\,t_s) \tag{19}$$

$$110 + 35 + 110 = 3.5\,(0.75 \times 10 + 10 + 0.75 \times 10 + 0.5\,t_s)$$

$$t_s = 95.7\,s.$$

$$f_{max} = \frac{3600}{t_{st} + t_r + t_b + t_s}$$

$$f_{max} = \frac{3600}{10 + 10 + 10 + 95.7} = 28.64\,\text{per hour}.$$

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Thank You

Numerical Problems on dc Motor Drives

Tutorial-3

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1 Numerical Problems

Numerical Problem-1

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

Solution-1

- Since the $T \propto I_a$, motor armature current when regenerating

$$I_{a2} = 0.8 \times 200 = 160\,A. \tag{1}$$

$$E_1 = 220 - 200 \times 0.06 = 208\,V. \tag{2}$$

$$E_2 = \frac{N_2}{N_1} E_1 = \frac{600}{800} \times 208, = 156\,V. \tag{3}$$

- Internal voltage of the variable voltage source is

$$= 156 - 160\,(0.06 + 0.04) = 140\,V. \tag{4}$$

Numerical Problem-2

A 220 V dc series motor runs at 1000 from (clockwise) and takes an armature current of 100 A when driving a load with a constant torque. Resistances of the armature and field windings are 0.05 Ω each. Now, the series motor is operated under dynamic braking at twice the rated torque and 800 rpm. Calculate the value of braking current and resistor. Assume linear magnetic circuit.

Solution-2

- Since

$$T_1 = K_f I_{a1}^2; \quad T_2 = K_f I_{a2}^2 \tag{5}$$

$$I_{a2} = I_{a1}\sqrt{T_2/T_1} = 100\sqrt{2} = 141.4\,A.$$

$$E_1 = K_e I_{a1} N_1; \quad E_2 = K_e I_{a2} N_2 \tag{6}$$

$$E_2 = \frac{I_{a2}}{I_{a1}} \times \frac{N_2}{N_1} \times E_1 \tag{7}$$

$$E_2 = \frac{141.4}{100} \times \frac{800}{1000}(220 - 100 \times 0.1) = 237.55\,V.$$

- Now,

$$E_2 = I_{a2}(R_B + 0.1) \tag{8}$$

$$237.55 = 141.4(R_B + 0.1)$$

$$R_B = 1.58\,\Omega.$$

Numerical Problem-3

A 220 V, 970 rpm, 100 A dc separately excited motor has an armature resistance of 0.05 Ω. It is braked by plugging from an initial speed of 1000 rpm. Calculate
(a) resistance to be placed in armature circuit to limit braking current to twice the full load value
(b) braking torque, and
(c) torque when the speed has fallen to zero.

Solution-3

- At 970 rpm,

$$E = 220 - 0.05 \times 100 = 215\,V. \tag{9}$$

- At 1000 rpm,

$$E = \frac{1000}{970} \times 215 = 221.65\,V. \tag{10}$$

- (a) For plugging operation

$$\begin{aligned} R_B + R_a &= \frac{E + V}{I_a} = \frac{221.65 + 220}{200} = 2.21\,\Omega. \\ R_B &= 2.21 - 0.05 = 1.16\,\Omega. \end{aligned} \tag{11}$$

- (b) braking torque is

$$T = \frac{E \times I_a}{\omega_m} = \frac{221.65 \times 200}{1000 \times 2\pi/60} = 423.3\,N - m. \tag{12}$$

- (c) At aero speed $E = 0$

$$I_a = \frac{V}{R_B + R_a} = \frac{220}{2.21} = 99.55\,A. \tag{13}$$

- As $T \propto I_a$,

$$T = 423.3 \times \frac{99.55}{200} = 210.7\,N - m. \tag{14}$$

Numerical Problem-4

A 220 V, 500 A, 600 rpm separately excited motor has armature and field resistance of 0.02 and 10 Ω, respectively. The load torque is given by the expression $T_L = 2000 - 2N$, $N-m$, where N is the speed in rpm. Speeds below the rated are obtained by armature voltage control and speeds above the rated are obtained by field control.
(i) Calculate motor terminal voltage and armature current when the speed is 450 rpm.
(ii) Calculate field winding voltage and armature current when the speed is 750 rpm.

Solution-4

- (i) At 450 rpm,

$$T_L = 2000 - 2 \times 450 = 1100\,N - m. \tag{15}$$

- At rated operation,

$$E_1 = 220 - 500 \times 0.02 = 210\,V. \tag{16}$$

- Rated torque is given as

$$T = \frac{E_1\,I_{a1}}{\omega_{m1}} = \frac{210 \times 500}{600 \times 2\pi/60} = 1671\,N - m. \tag{17}$$

- For a torque of 1100 N-m, $I_{a2} = \frac{1100}{1671} \times 500 = 329\,A.$
- At 450 rpm,

$$E_2 = \frac{450}{600} \times 210 = 157.5\,V. \tag{18}$$

$$V = E_2 + I_{a2}\,R_a = 157.5 + (329 \times 0.02) = 164\,V. \tag{19}$$

Solution-4

- At 750 rpm,

$$T_L = 2000 - 2 \times 750 = 500\, N - m. \tag{20}$$

- At this operating point, let the flux and armature current be $\phi\prime$ and $I_a^{'}$, respectively. Then

$$K_e \phi^{'} I_a^{'} = 500 \tag{21}$$

- From rated operation

$$K_e \phi_1 = \frac{210}{600 \times 2\pi/60} = 3342. \tag{22}$$

- Further at 750 rpm,

$$\omega_m^{'} = \frac{750}{60} \times 2\pi = 78.54 rad/s. \tag{23}$$

$$V = K_e \phi^{'} \omega_m^{'} + I_a^{'} R_a \tag{24}$$

$$220 = 78.54\, K_e \phi^{'} + 0.02\, I_a^{'}$$

Solution-4

- Substituting from Eq. 21

$$220 = 78.54 \times \frac{500}{I_a^{'}} + 0.02\, I_a^{'} \tag{25}$$

$$0.02\, I_a^{'\,2} - 220\, I_a^{'} + 39270 = 0. \tag{26}$$

- This equation has solution 181.5 A and 21647 A. Ignoring the unfeasible value gives

$$I_a^{'} = 181.5\, A. \tag{27}$$

- From Eq. 21

$$K_e\, \phi^{'} = \frac{500}{181.5} = 2.755 \tag{28}$$

$$\text{field voltage} = 220 \times \frac{K_e\, \phi\prime}{K_e\, \phi_1} = \frac{2.755}{3.342} = 181.3\, V. \tag{29}$$

Numerical Problem-5

A 2-pole separately excited dc motor has the ratings of 220 V, 100 A and 750 rpm. Resistance of the armature is 0.1 Ω. The motor has two field coils which are normally connected in parallel. It is used to drive a load whose torque is expressed as $T_L = 500 - 0.3N$, N-m where N is the motor speed in rpm. Speeds below and above rated are obtained by armature voltage control and by connecting the two field windings in series respectively.

(i) Calculate the motor armature current and speed when the armature voltage is reduced to 110 V.

(ii) Calculate the motor speed and current when field coils are connected in series.

Solution-5

- At rated operation,

$$E_1 = 220 - 100 \times 0.1 = 210\,V.$$

$$\omega_{m1} = \frac{750}{60} \times 2\pi = 25\pi.$$

$$K_e\,\phi_1 = K = \frac{E_1}{\omega_{m1}} = \frac{250}{25\pi} = 2.674. \tag{30}$$

- (i) Let the motor speed and current be N_2 and I_{a2}, respectively.

$$E_2 = K\,\omega_{m2} = 2.674 \times \frac{N_2 \times 2\pi}{60} = 0.28\,N_2$$

$$V = E_2 + I_{a2}\,R_a \tag{31}$$

$$110 = 0.28\,N_2 + 0.1\,I_{a2}. \tag{32}$$

- Since, $T = T_L$

$$K\,I_a = 500 - 0.3\,N \tag{33}$$

$$2.674\,I_{a2} = 500 - 0.3\,N_2$$

$$500 = 0.3\,N_2 + 2.674\,I_{a2}. \tag{34}$$

- Simutaneous solution of Eq. 32 and 34 gives

$$I_{a2} = 148.9\,A \quad \text{and} N_2 = 339.7\,rpm. \tag{35}$$

(ii) When filed coils are connected in series

$$K = \frac{2.674}{2} = 1.337. \tag{36}$$

- If armature current and speeds are I_{a3} and N_3

$$E_3 = 1.337\,N_3 \times \frac{2\,\pi}{60} = 0.14\,N_3 \tag{37}$$

$$V = E_3 + I_{a3}\,R_a^{'}$$

$$220 = 0.14\,N_3 + 0.1\,I_{a3} \tag{38}$$

- Since $T = T_L$

$$1.337\,I_{a3} = 500 - 0.3\,N_3 \tag{39}$$

$$500 = 0.3\,N_3 + 1.33\,I_{a3}. \tag{40}$$

- Simultaneous solution of Eqs. 38 and 40 yields

$$I_{a3} = 25.48\,A \quad \text{and} N = 15853.2\,rpm. \tag{41}$$

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