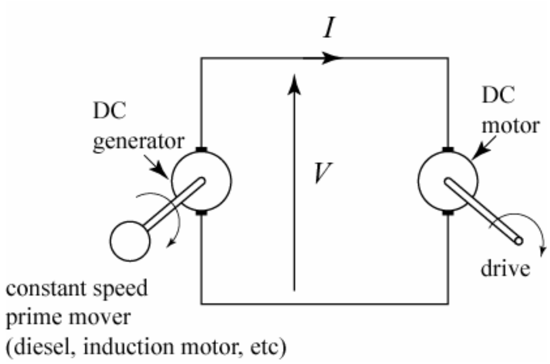
Lecture 10
DC Motor Control

Objectives

- To introduce the basic principles of DC machines
- To consider the operation of DC machines in the motoring, generating and braking modes
- To introduce the principles of variable-speed drives as applied to DC machines
- To examine the control of drives based on DC machines
- To consider a specific application of DC machine control, namely traction

Introduction

- 1896 – Harry Ward-Leonard proposed variable speed drive in which DC generator driven by diesel engine provided DC supply for motor

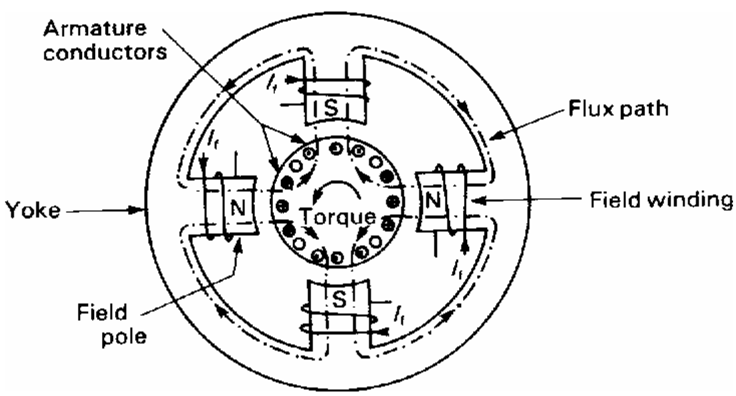


- System had dominating effect and use of controlled DC machine became very fashionable
- Hence, even with increasing availability of power electronic switching devices, DC machines continued to dominate variable speed market until 1980s
- From then, growth in availability and rating of self-commutating devices such as GTO thyristors, power transistors and insulated gate bipolar transistors (IGBTs) has meant that drives based on use of AC induction machines have become increasingly common

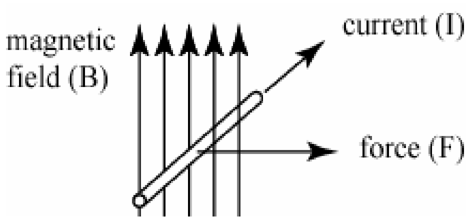
- Recently, microprocessor-based digital control systems have replaced analogue controllers in many applications – increased sophistication of operation, facilitating use of other types of machine such as stepper motor and switched reluctance motor
- Inspite of increasing popularity of AC machines and other forms, in this course time limitations mean we will concentrate on DC machine control

DC Machines Basic Principles

- Conventional DC machine consists of stationary field winding and rotating armature winding:

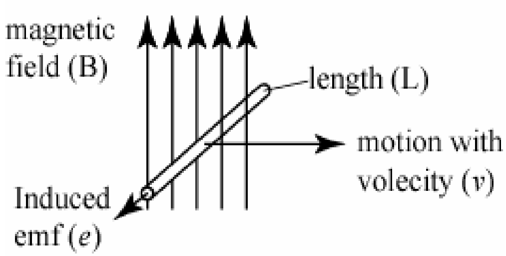


- Field winding supplied with DC current to produce static magnetic field within air gap
- Magnetic field interacts with current in armature conductors to produce torque to rotate armature
- Behaviour of DC machines determined by two fundamental laws relating to current carrying conductor moving in electric field:
  - 1) Conductor carrying current I Amps in magnetic field B Tesla



Force on conductor: $F = I \times B$

- 2) Conductor of length L metres, moving with velocity v ms^{-1} in magnetic field of strength B Tesla:

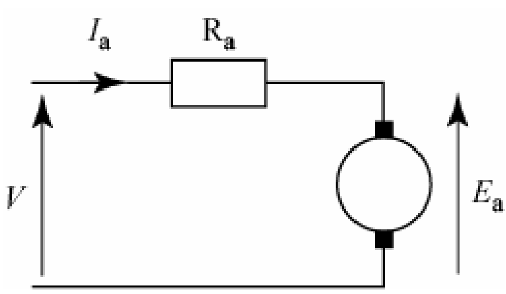


$$e = B \times L \times v$$

Voltage induced in conductor:

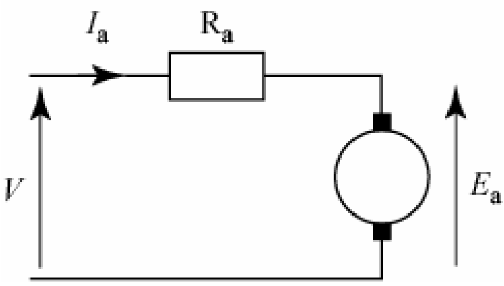
- To sustain torque due to current in armature windings and magnetic field produced by field windings, armature current distribution relative to field must be maintained constant, irrespective of rotor position
  - Achieved by commutator which acts to reverse direction of current in armature conductors as they pass from under one field pole to next
- As armature conductors are moving through magnetic field produced by field winding they have voltage, or back EMF, E_a induced in them which is function of strength of field and speed of rotation
- Back EMF will oppose applied voltage when DC machine is acting as motor and provide source voltage when it is used as generator

- Motoring mode
  - DC machine draws power from DC source and electrical torque developed by machine acts to rotate armature against mechanical load:



$$V = E_a + I_a R_a$$

- Generator mode
  - power is delivered by machine to DC load and electrical torque developed opposes mechanical torque driving armature



$$E_a = V + I_a R_a$$

- The general equation for the armature has the form:

$$E_a = V \pm IR$$

- For conductor moving in magnetic field, back EMF given by:

$$E_a = K\phi\omega$$

ϕ is the flux per pole

ω is the rotational speed of the armature in radians per second

K is a constant

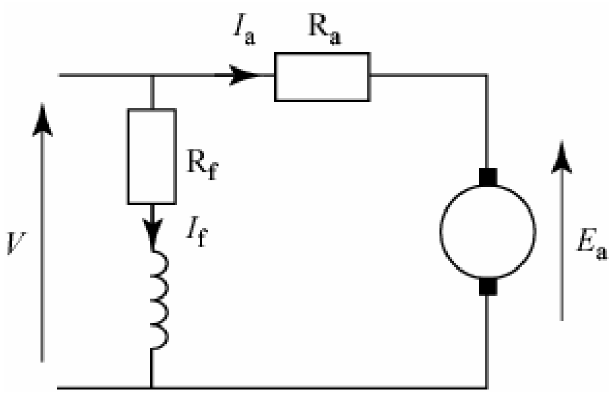
- Torque developed given by: $T = K\phi I_a$
- Mechanical power in terms of electrical quantities: $P = T\omega = K\phi I_a \omega$

$$P = K\phi I_a E_a / (K\phi) = E_a I_a$$

- i.e. Mechanical output power = electrical input power

Shunt and series field windings

- Shunt-connections: field supplied from same supply as armature:



  - Field current independent of armature current

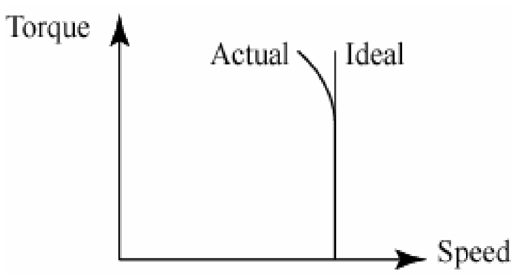
- Torque-speed characteristic:

$$V = E_a + I_a R$$

  - Assuming zero internal losses: $R = 0 \therefore V = E_a$

$$V = K\phi\omega \quad \omega = \frac{V}{K\phi}$$

  - Shunt-connected machine operates ideally in <u>constant speed mode</u> with speed dependent on applied armature and field voltages
  - Practical torque-speed characteristic:

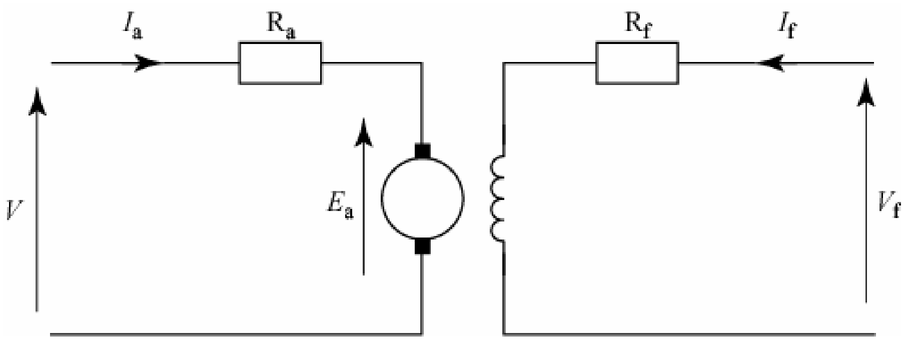


- Armature current

$$I_a = \frac{T}{K\phi}$$

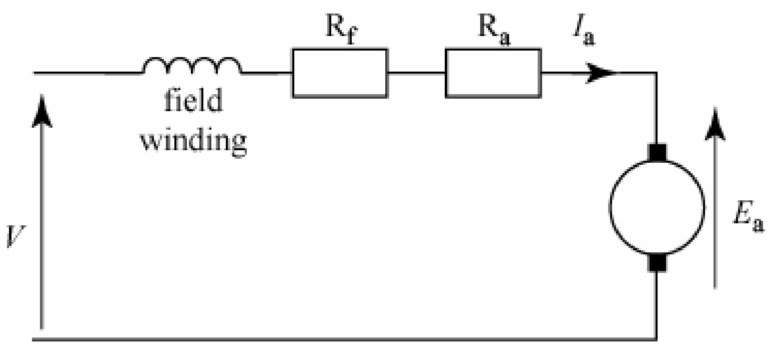
- Hence as torque increases, so does I_a; this causes increased internal losses reducing speed at high torque

- Separately excited DC machine: field has its own independent supply:



- Operation similar to shunt-connected machine but with independent control of armature voltage E_a and field ϕ

- Series-connection: field and armature windings connected in series:



- Armature current flows through field winding
- Let field flux be given be:

$$\phi = K_f I_a$$

$$T = K\phi I_a = KK_f I_a^2 \quad \therefore I_a = \sqrt{\frac{T}{KK_f}}$$

- Governing equation:

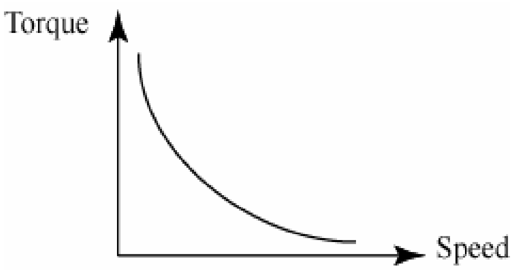
$$V = I_a\left(R_a + R_f\right) + E_a$$

- Ignore losses; let R_a = 0:

$$\begin{aligned} V &= I_a R_f + E_a \\ &= I_a R_f + K\phi\omega \\ &= I_a\left(R_f + KK_f\omega\right) \\ &= \sqrt{\frac{T}{KK_f}}\left(R_f + KK_f\omega\right) \end{aligned}$$

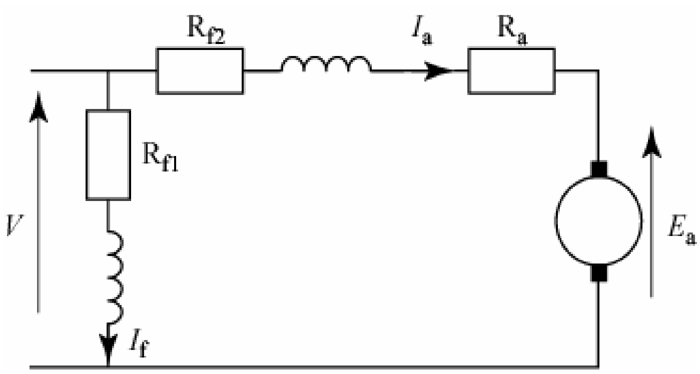
- By rearranging, we obtain:

$$T = \frac{V^2 KK_f}{\left(R_f + KK_f\omega\right)^2}$$



- Can use diverter resistance and compound windings

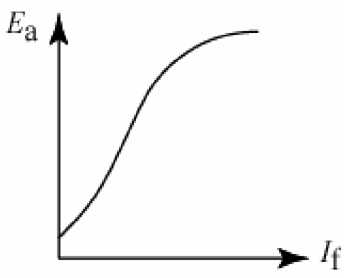
- A compound wound DC machine contains both series and shunt (or separately excited) field windings



- The resulting field can either be the sum (cumulative compounding) or the difference (differential compounding) of the applied series and shunt fields.

Open-circuit characteristic

- Open-circuit characteristic or excitation curve of DC machine



- Driving armature at constant speed and recording open-circuit voltage E_a over full range of field current I_f
- Shape of curve determined by magnetic characteristic

- Features of open circuit characteristic:
  - Small voltage with zero applied field – results from residual flux remaining in core once main field is removed
  - Open-circuit voltage not linear function of field current – ferro-magnetic materials saturate at higher values of field
- Only a single curve is needed to describe the operation of the DC machine over the whole of its speed range since, for constant field:

$$\frac{E_{a1}}{E_{a2}} = \frac{\omega_1}{\omega_2} = \frac{n_1}{n_2}$$

$$E_a = K\phi\omega$$

- ω_1 and ω_2 are any two machine speeds in radians/s and n_1 and n_2 are machine speeds measured in revolutions per minute; E_{a1} and E_{a2} are open-circuit armature voltages for these speeds
- Open-circuit voltage or back EMF can be calculated at any speed

Operation in motoring mode

- Field control
  - The equations we derived earlier were as follows:

$$V = E_a + IR \quad \text{and} \quad E_a = K\phi\omega$$

  - Neglecting armature resistance:

$$V = K\phi\omega$$

  - If V is constant, then speed ω can be controlled by ϕ:

$$\omega = \frac{V}{K}\frac{1}{\phi}$$

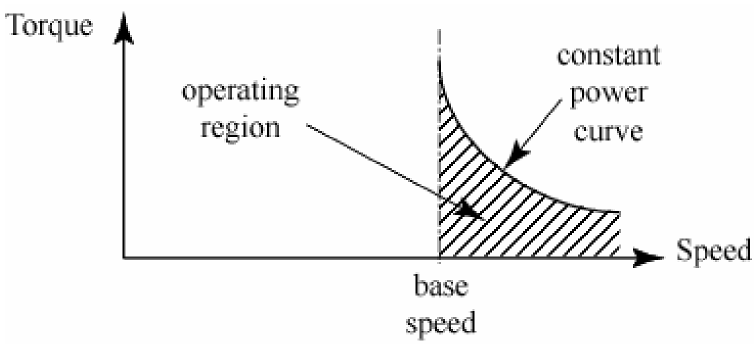
  - Limiting conditions: max armature current; max armature voltage

$$P_{\max} = V_{\max} I_{a,\max} = T\omega$$

  - At limit:

$$T = \frac{V_{\max} I_{a,\max}}{\omega}$$

  - DC machine operates with constant power limit
- Torque-speed envelope:



- Min speed determined by max armature voltage and max field current
- Speed variation of order of 4 or 5 to 1 typically obtainable for small machines, falling to around 2 to 1 for large machines

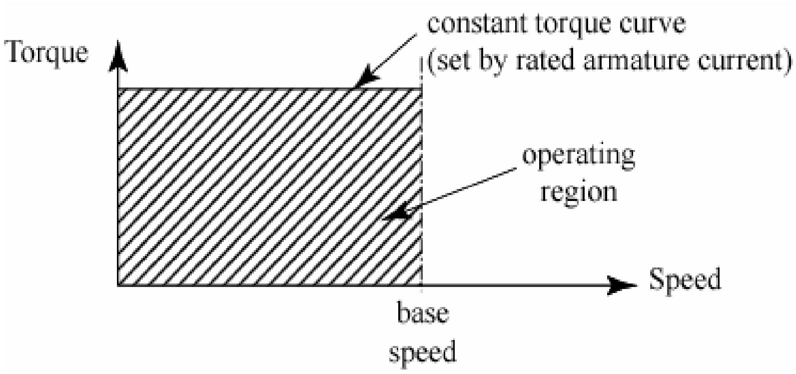
- Armature voltage control
  - Previous expression: $V = K\phi\omega$
  - If field ϕ held constant, speed can be controlled by armature voltage

$$\omega = \frac{1}{K\phi} V$$

  - Applying same restriction on maximum armature current:

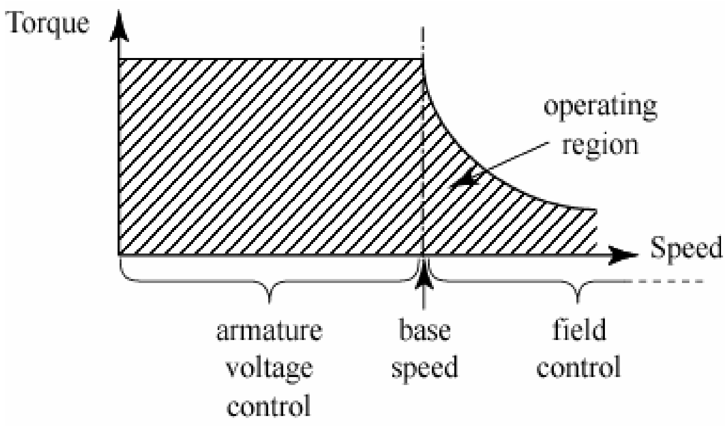
$$T = \frac{VI_{a,\max}}{\omega} = \frac{VI_{a,\max}}{V/(K\phi)} = K\phi I_{a,\max}$$

- Hence, at limit, DC motor operates with constant torque:



- Maximum operating speed achieved with maximum applied armature voltage and maximum field current; speed range around 100:1

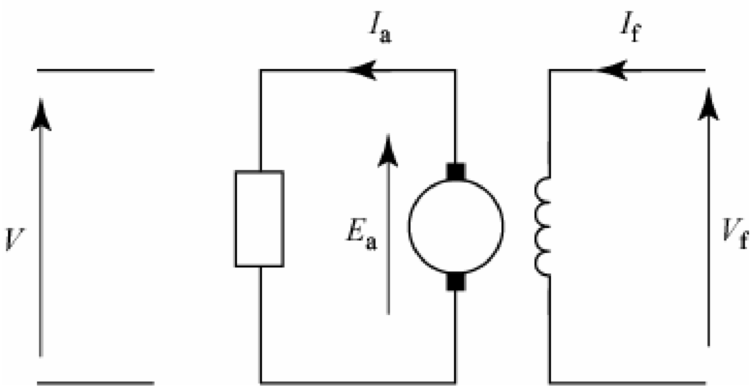
- Operating envelope for field and armature voltage control:



Braking

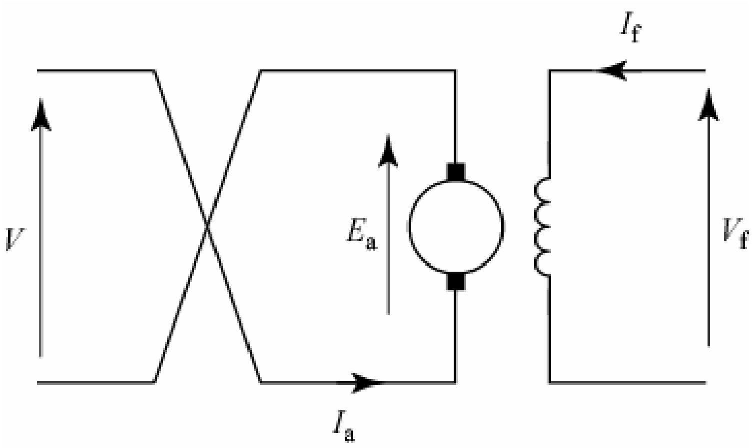
- DC motor will be required both to accelerate and decelerate
- Deceleration can be assisted by three forms of electrical braking

- Resistive braking
  - Armature disconnected from supply and connected to braking resistor



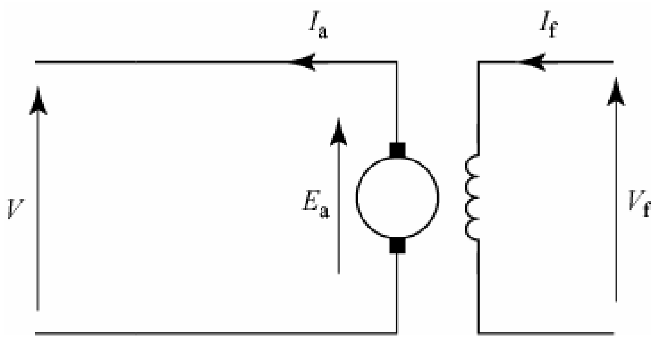
  - EMF drives current through braking resistor, dissipating energy stored

- Reverse supply braking



  - Back EMF adds to supply voltage and drives reverse current through armature
  - Reverse torque decelerates motor
  - Current limiting resistor normally included in series with armature

- Armature voltage must be removed once speed has been reduced to zero to prevent direction of rotation from being reversed
- Regenerative braking
  - If field adjusted so that back EMF > voltage applied to armature machine will act as generator transferring energy from mechanical system to DC supply



  - Maximum allowable field limited by field voltage supply and maximum permitted field current

DC machine dynamics

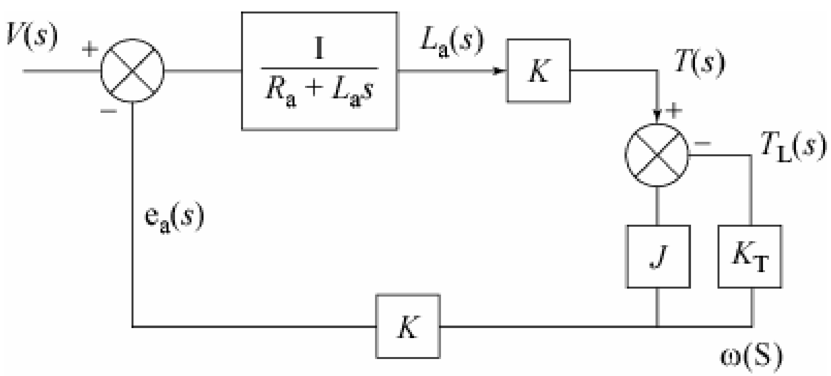
- Considered DC machine in terms of steady-state performance
- In practice, dynamic behaviour is important
- Machine equations, modified to include dynamic term:

Equations for	Static Case	Dynamic Case
Armature circuit	$V = E_a \pm I_a R_a$	$V = E_a \pm \left(I_a R_a + L_a \frac{dI_a}{dt} \right)$
Load	$T = K\phi I_a = T_L$	$T = K\phi I_a = T_L + J\frac{d\omega}{dt}$

Equations for	Static Case	Dynamic Case
Back EMF	$E_a = K\phi\omega$	$E_a = K\phi\omega$
Field Circuit	$V_f = I_f R_f$ $\phi = f(I_f)$	$V_f = I_f R_f + L_f \dfrac{dI_f}{dt}$ $\phi = f(I_f)$

Where T_L is the load torque
J is the rotary inertia
L_a is the armature inductance
R_f is the resistance of the field circuit
L_f is the inductance of the field circuit

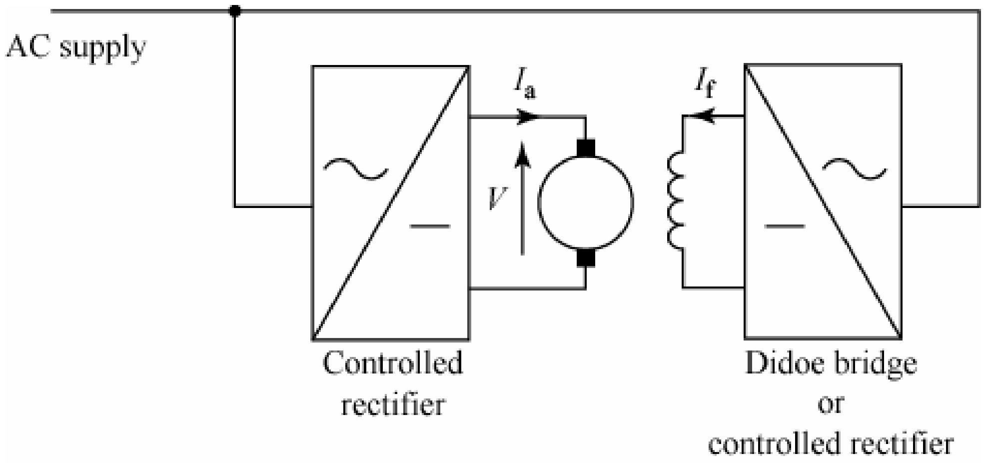
- Representation of dynamic equations by block diagram showing inter-relationships between variables:



- Solution using Laplace transform techniques

Variable speed DC drives

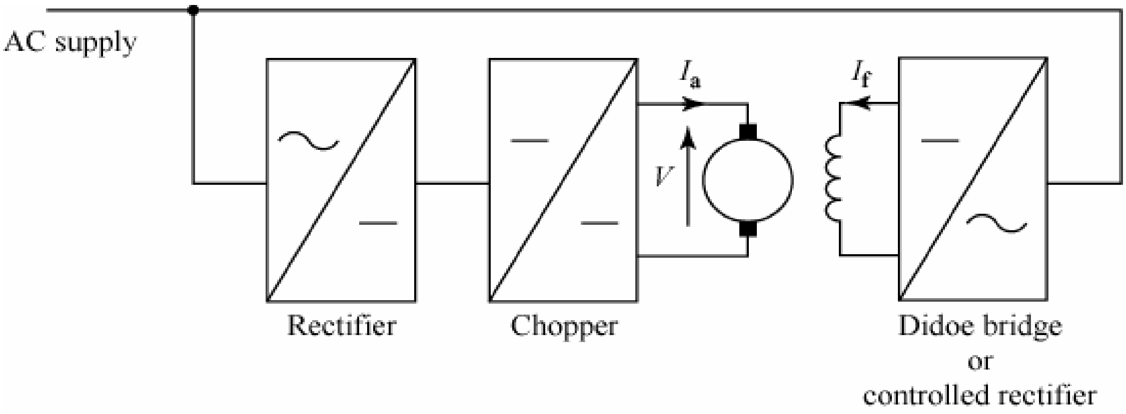
- Most common form based on control of armature voltage using fully-controlled or half-controlled converter:



- If regenerative operation is required, converter must be fully-controlled

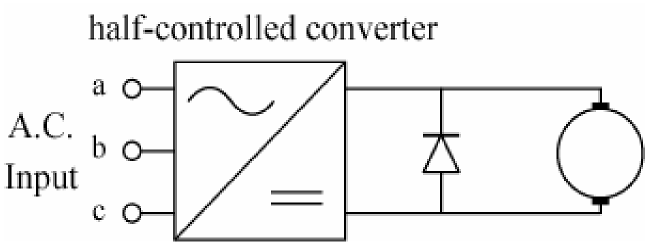
- Majority of converter-based drives are intended for operation with DC machine having sufficient armature inductance to maintain armature current approximately constant over one cycle of supply voltage waveform
- Extra inductance may be added in series with armature of machine
- DC machines for variable speed operation from controlled converter designed with laminated field poles and increased armature inductance

- Alternative is combination of uncontrolled converter with a DC chopper:



- DC chopper would also be used where DC source already available

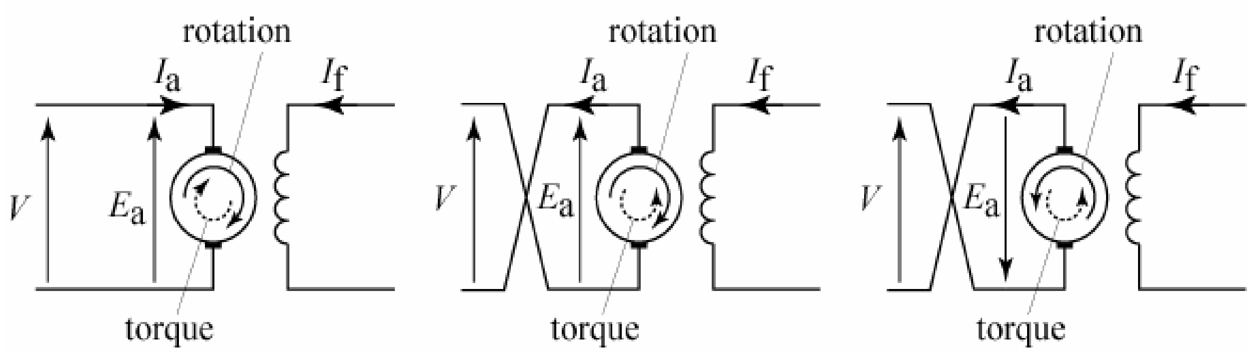
- For lower rated drives using half-controlled converters, commutating diode included



- Prevents reversal of converter output voltage and results in improved commutation and reduced armature current ripple
- Armature current may become discontinuous under conditions of light load or on starting

Reversing drives

- Operating modes during reversal:

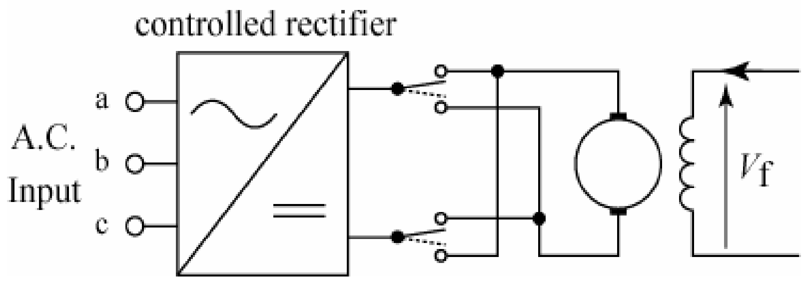


Velocity:	Forwards	Forwards	Backwords
Acceleration:	Accelerating	Decelerating	Accelerating
Power:	To load	From load	To load
Mode:	Motoring (Forward)	Regenerating (braking)	Motoring (Reverse)

- Direction of torque linked direction of current flow I_a; direction of rotation linked to polarity of back EMF E_a
- Reversal of drives may be achieved using a number of techniques which have distinct advantages and disadvantages

Contactor reversal

- Direction of rotation of DC motor can be reversed by reversing either armature voltage or field current

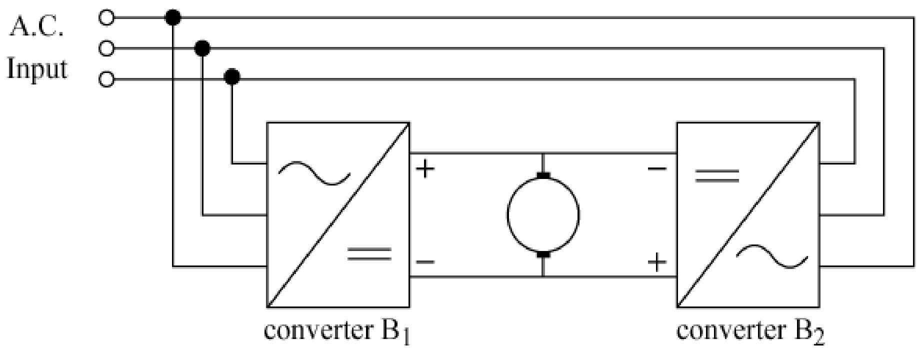


- Can be used with either fully-controlled or a half-controlled converter

- When fully-controlled converter used, regenerative braking is possible
- Operation: speed of machine in original direction and armature current first reduced to zero; then contactor can be operated to reverse direction of applied armature voltage
- Use of contactor introduces period of around 0.2s over which no torque is developed
- Acceptable for drives such as presses, hoists, lathes and marine propulsion where reversals are infrequent
- Applications, such as steel strip mills and paper mills require rapid reversal

Dual converter reversing drive

- Full 4-quadrant operation can be achieved by using pair of bridges with opposite polarities:

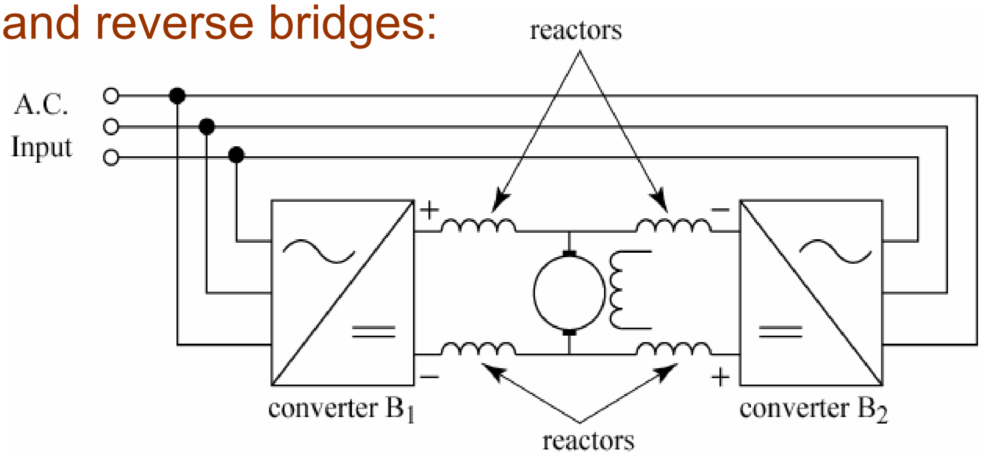


- Assume initial operation in motoring mode with bridge B_1 conducting:
  - Firing angle of bridge B_1 is increased to turn-off current in bridge

  - Bridge is B_1 turned off
  - Bridge B_2 takes over in inverting mode and machine regenerates, returning energy to DC supply
  - As speed of machine reduces, firing angle of bridge B_2 is reduced to give zero voltage at or near to zero speed
  - Firing angle of bridge B_2 is further reduced to control acceleration of machine in reverse direction
  - Machine now running as a motor in <u>reverse direction</u>
- Since it is not permissible to fire both bridges together, there must be finite dead zone in which both converters are not operating

Dual converter configuration with current limiting reactors

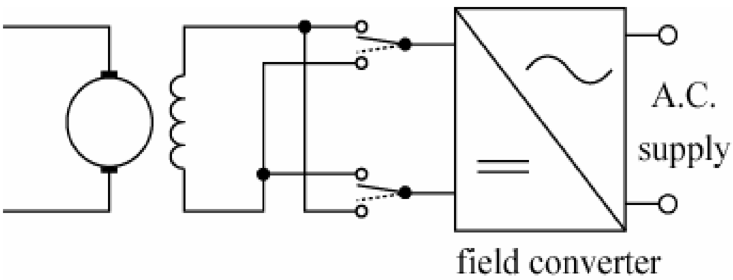
- Further improvement in performance achieved by including current limiting reactors between forward and reverse bridges:



- Bridges can now conduct simultaneously, reducing time required for reversal
- Eliminates occurrence of dead zone

Field reversal

- Field reversal can be achieved by means of dual bridges or contactors:

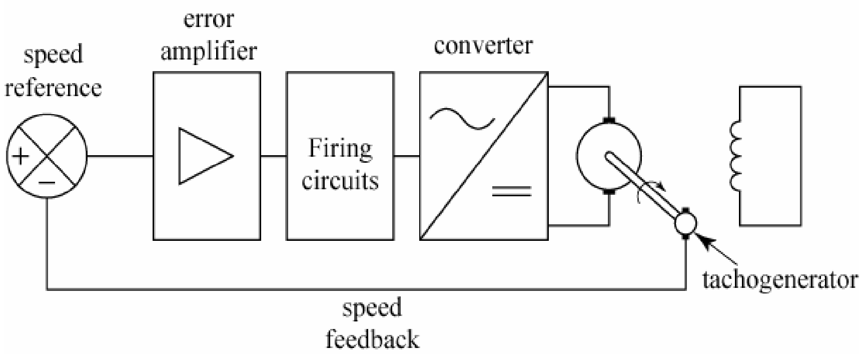


- Reversal of field current can only take place relatively slowly because of need to remove stored energy in field prior to current reversal, introducing delays of about 1s before torque reversal

DC motor control

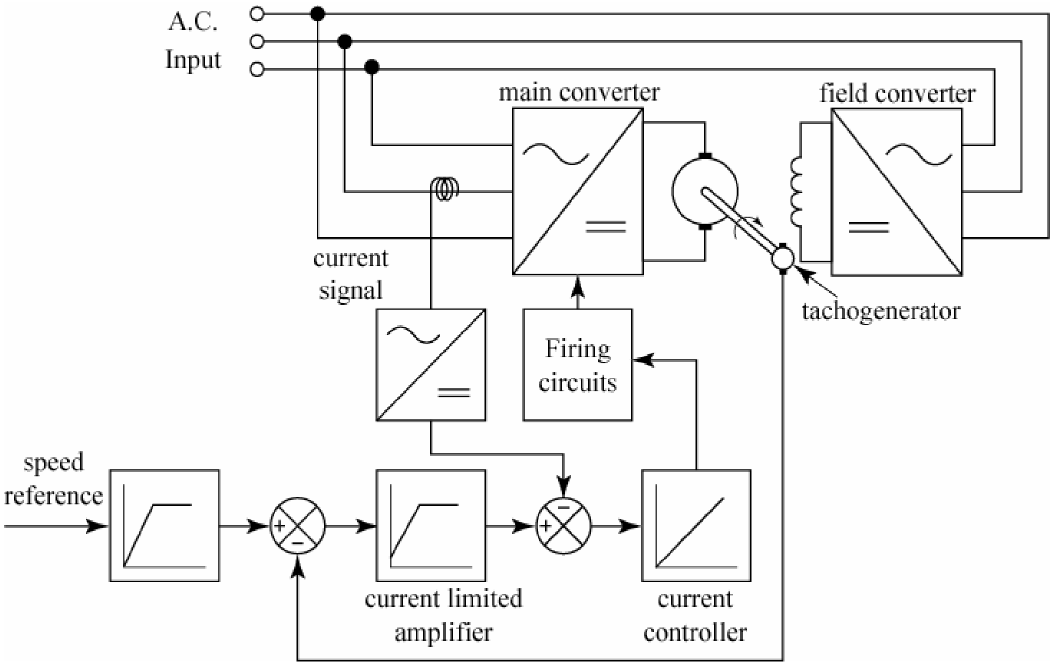
- Drive control system requirements:
  - To respond to changes in demand speed or torque
  - To provide start-up and shut-down procedures
  - Operation independent of fluctuations in supply conditions
  - To optimise the operating conditions for best performance
- Further requirements:
  - To provide protection against overloads and faults
  - To maintain a check on drive status and performance
  - To synchronise the operation of a number of drives
  - To operate reversing drives

- Basic control system:



  - Information on output speed fed back to difference element
  - Output of difference element amplified by error amplifier – used to control converter firing circuits
  - Low armature resistance → excessive converter currents
  - Means of limiting armature current usually included in control circuit

- Advanced DC machined speed control system:



- Typical analogue controller for single quadrant drive
- Demand or reference speed ω_r fed to comparator via ramp generator to smooth out and limit effect of sudden or large changes in demand speed
- Comparator compares reference with speed ω_m from tachogenerator
- Comparator error signal to current limited amplifier which restricts maximum error signal and hence maximum armature current
- Current limited amplifier output then compared with armature current I_a
- Armature current obtained by means of AC transformer and rectifier in converter supply
- Second comparator output used to control firing angle of converter
- Analogue controllers provides speed stability of about 0.1%

- Digital control systems
  - Digital control systems based on microprocessors
  - Alternatively on application specific integrated circuits (ASICs)
  - Advantages:
    - Greater precision
    - Flexibility
    - Consistency
    - Stability
    - Noise immunity
    - Speed stability $\approx$ 0.01%
  - Have largely replaced analogue systems for many applications

- Digital systems enable precise speed matching or controlled speed ratios between two or more motors by use of common speed reference
- Control precise phase relationship between shafts of individual motors
- Systems with precise phase relationship are referred to as an electronic gearbox
- Development of ASIC-based control implementations combined with hybrid thick film technologies offers opportunity for embedding complete controller within frame or enclosure of DC machines, simplifying overall system configuration

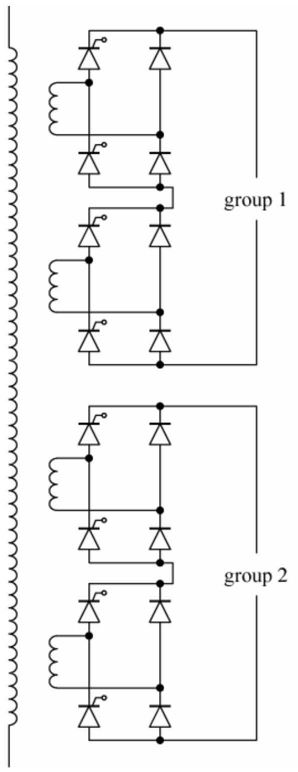
Traction drives

- General principles:
- Traction drives traditionally used DC series motor with its high torque capability at low speeds
- Early systems: on-board rectifiers and tap-changing transformers – up to 30% ripple in motor supply current, smoothed by inductance of machine armature circuit
- Advent of power electronics:
  - Resulted in introduction of traction systems based on separately or shunt-excited DC motors or AC motors
  - Increased flexibility of operation by allowing designer to optimise performance over full operating envelope of machine

  - Incorporation of microprocessor-based controllers has enabled optimisation of tractive effort by allowing operation close to limit of adhesion
  - Greater use made of regenerative braking
- Operation of system from start-up:
  - Full field applied to both motors; one converter in each group is fired
  - Firing angle of active converter is controlled to provide constant motor current in order to provide constant torque and therefore constant acceleration
  - Motor current flows through diodes of inactive bridge
  - As back EMF increases, firing angle of conducting bridge is brought towards zero corresponding to maximum output voltage

- Second converter now brought into operation; firing angle gradually reduced towards zero, still maintaining constant torque and acceleration
- Once firing angle of second converter has reached zero, both converters are operating at maximum output voltage
- Further control by means of the field current

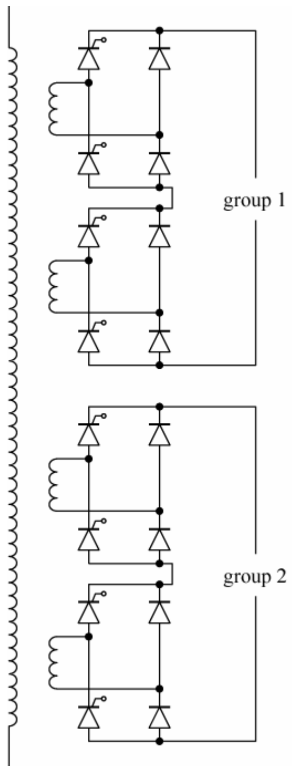
- Typical converter arrangement for locomotive traction drive:



- System provides separate control of motors on each bogie
- Half-controlled bridge converters connected in series are used operating from transformer secondaries
- Normal AC supply voltage for traction system on primary side of transformer is 25 kV single-phase
- Reversal achieved by means of reverse-parallel converters supplying field windings

Example on Traction Drives

- Traction drive based on system of half-controlled converters:



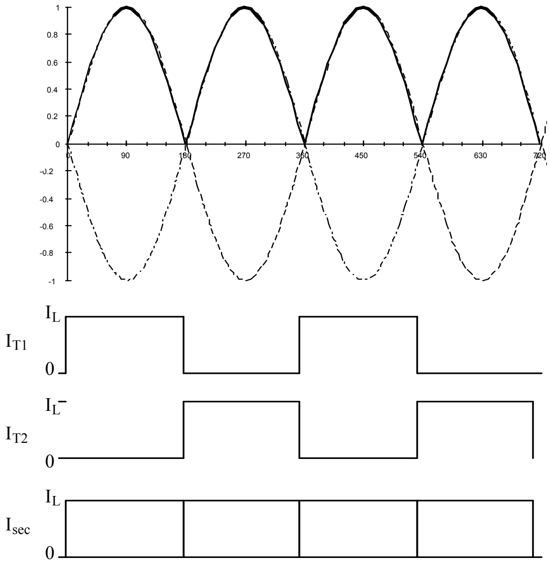
- Transformer primary winding fed from 25 kV, 50 Hz supply
- Transformer secondary windings feed each converter with supply of 320 V at 50Hz
- If motor voltage in each group is 3/4 of maximum and total motor current in each group is constant at 1200 A, estimate RMS value of current drawn 25 kV supply, neglecting all losses

- *Solution*
  - For single-phase half-controlled bridge converter, mean output voltage:

$$V_{mean} = \frac{V_m}{\pi}(1 + \cos\alpha)$$

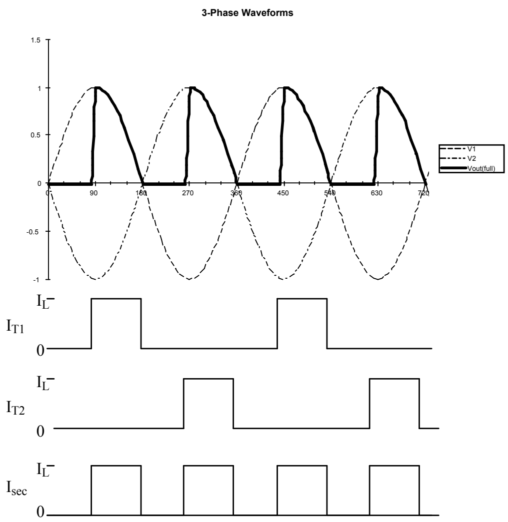
  - V_m is peak secondary voltage applied to converter and α is firing angle
  - For 3/4 maximum voltage at motors, one converter is fully conducting with $\alpha = 0^\circ$ and other converter is providing half maximum output voltage with $\alpha = 90^\circ$

- Output voltage and current waveforms for fully conducting bridge:



- Note: Load current flows continuously in transformer

- Output voltage and current waveforms for half conducting bridge:



- Load current flows only for 1/2 of the time in transformer secondary
- In other 1/2 of the time, load current flows through freewheeling diode

- Transformer ratio:

$$N = \frac{n_1}{n_2} = \frac{25000}{320} = 78.125$$

- Current in primary due fully conducting bridges:

$$I_{p1} = \frac{2 \times 320 \times 1200}{25000} = 30.72A$$

- Current in primary due to bridge operating at half maximum output voltage:

$$I_{p2} = \frac{2 \times 320 \times 1200}{25000} = 30.72A \text{ for } 50\% \text{ of the time}$$

- RMS current in 25 kV system is therefore given by:

$$I_{25kV,RMS} = \left[\frac{1}{2\pi} \left(\int_0^{\pi} 30.72^2 \, d\theta + \int_0^{\pi} 61.44^2 \, d\theta \right) \right]^{1/2}$$

$$= 48.57A$$

Summary

- Have introduced basic principles of DC machines and considered their operation in motoring, generating and braking modes
- Have introduced principles of variable-speed drives as applied to DC machines
- Have examine control of drives based on DC machines using basic and more advanced control systems
- Considered some specific application examples of DC machines drives