Power electronic and drives: ELEC 2208

Chapter 2: Power Electronic Control of DC Motor Drives

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Overview

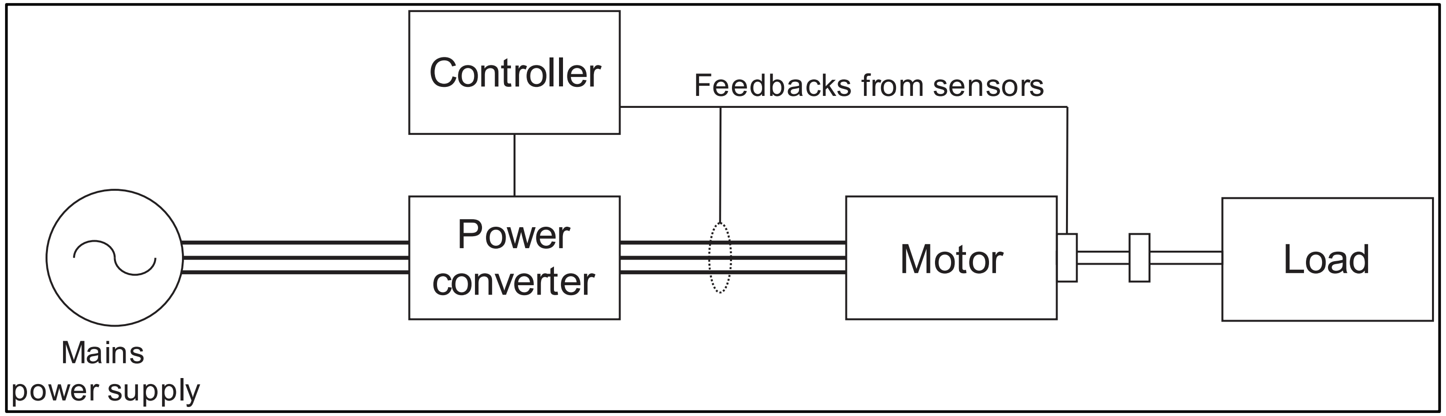
1. Chapter 2 covers the following basic definitions:
   - Introduction
   - Fundamentals of DC machines (general overview)
   - Speed control of separately excited DC motors
   - Chopper control of DC machines
   - Regenerative braking

2. Extended Summary of Chapter 2 is available on the Blackboard Shell

Learning outcomes

- Understand the main control structures used to control electric drives
- Explain basic structure of DC motor and show an overview of its type (brushed and brushless)
- Understand different modes of operation of DC motor
- Describe different techniques, with theoretical development, used to control speed of DC motor (e.g., flux control, voltage regulation and armature resistance control)

Basic components of electric drives

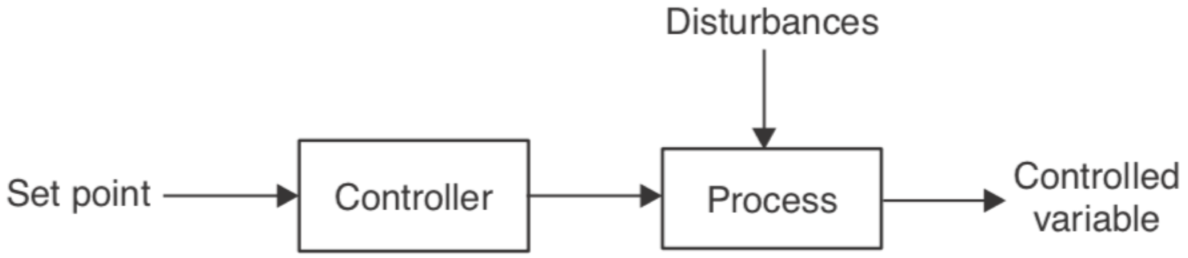


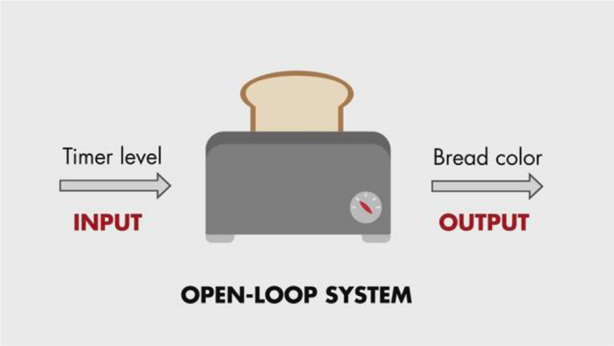
- A basic electric drive system consisting an electric source, a power-electronic converter (and auxiliary instrumentation and control components), and a load.

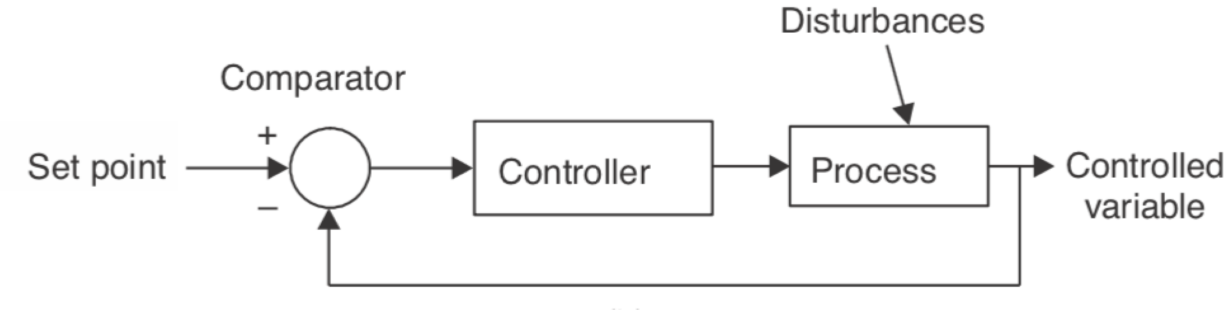
- Control of electrical machines can be performed in an open-loop manner or in a closed loop manner

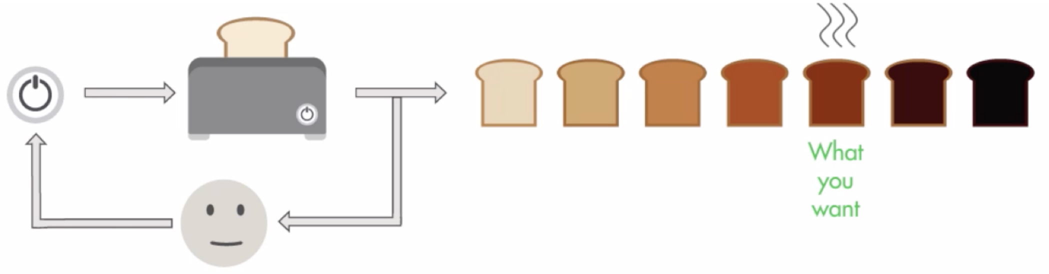
Techniques to control electric drives

Control of electrical machines can be performed in an <u>open-loop</u> manner or in a <u>closed loop</u> manner







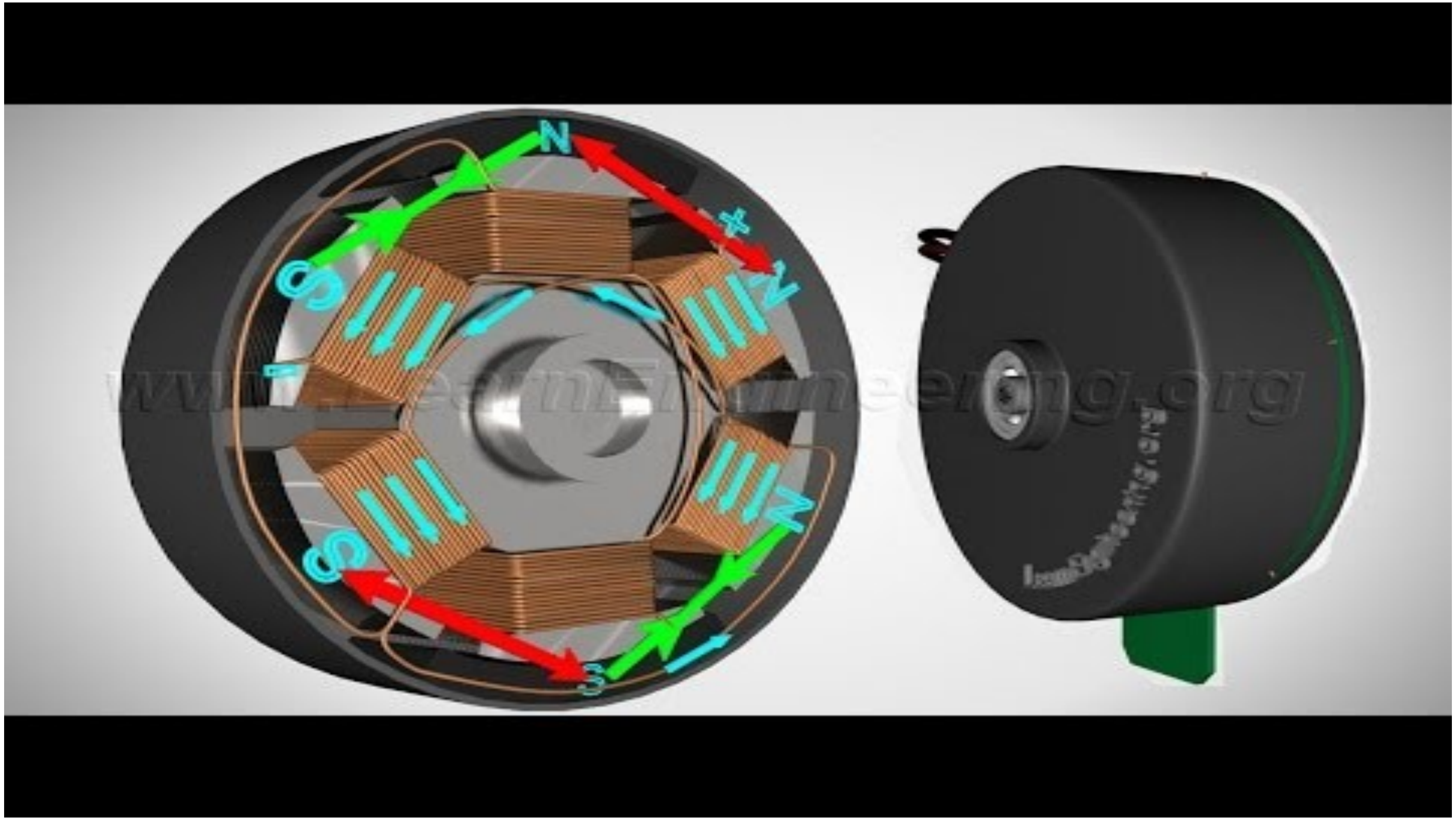


Techniques to control electric drives, ctd.

- **Open loop**: In an open-loop controller, also called a non-feedback controller, the control action from the controller is independent of the "process output", which is the process variable that is being controlled. It does not use feedback to determine if its output has achieved the desired goal of the input or process "set point". An open-loop system cannot engage in machine learning and also cannot correct any errors that it could make. It will not compensate for disturbances in the process being controlled
  https://www.electronics-tutorials.ws/systems/open-loop-system.html

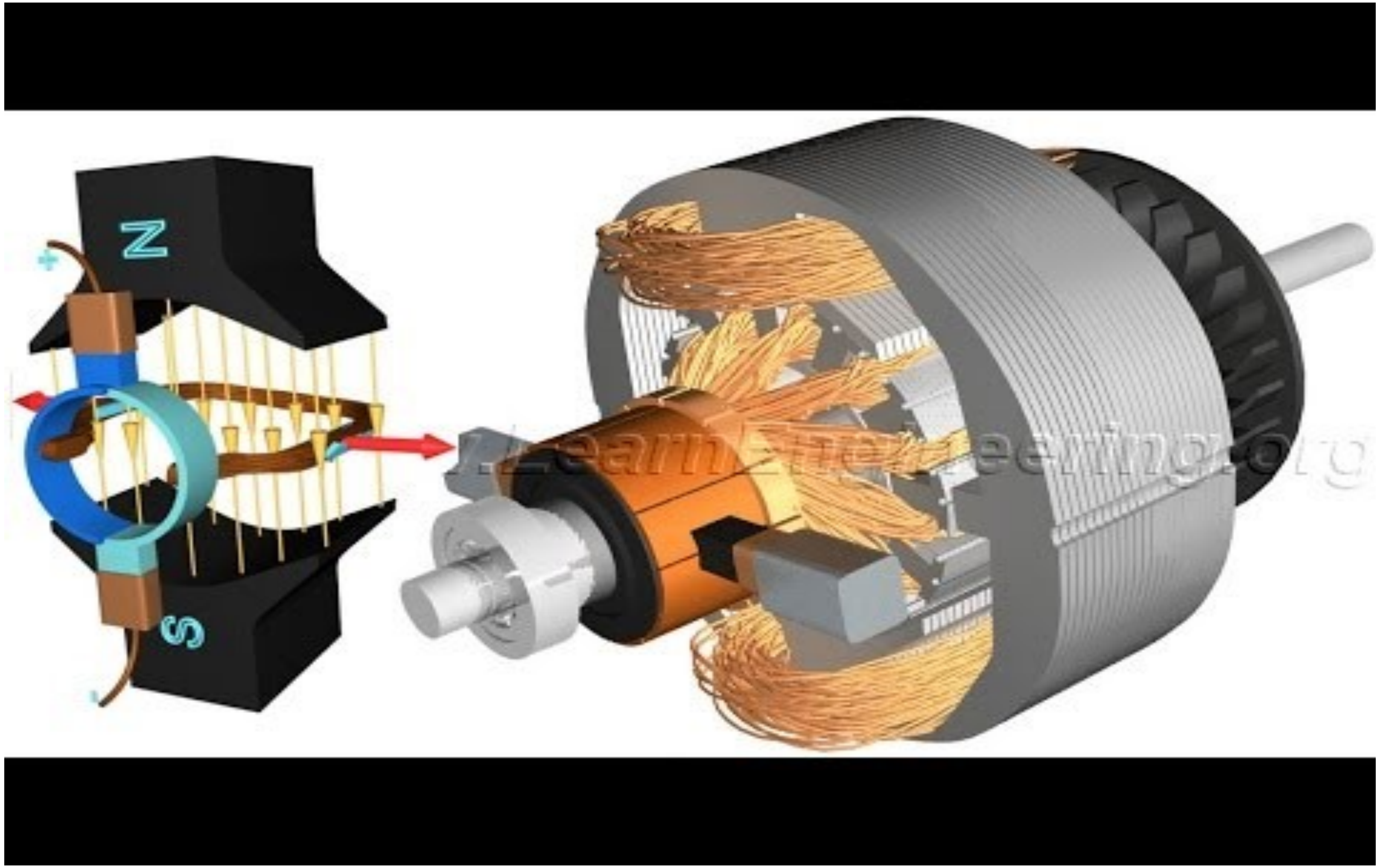
- **Closed loop**: control algorithm could be very complicated, but precise control of position, speed and/or torque in steady state as well as in transient is possible. In closed loop control, the control action from the controller is dependent on the process output. In the case of the boiler analogy this would include a thermostat to monitor the building temperature, and thereby feed back a signal to ensure the controller maintains the building at the temperature set on the thermostat. A closed loop controller therefore has a feedback loop which ensures the controller exerts a control action to give a process output the same as the "reference input" or "set point". For this reason, closed loop controllers are also called feedback controllers
  https://www.electronics-tutorials.ws/systems/closed-loop-system.html

General overview of DC motor drive: Brushed type



https://www.youtube.com/watch?v=bCEiOnuODac

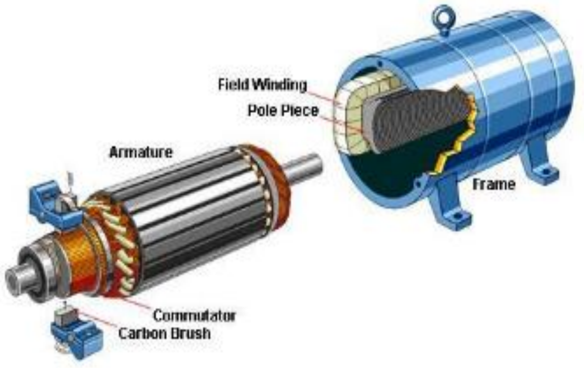
General overview of DC motor drive: Brushless type

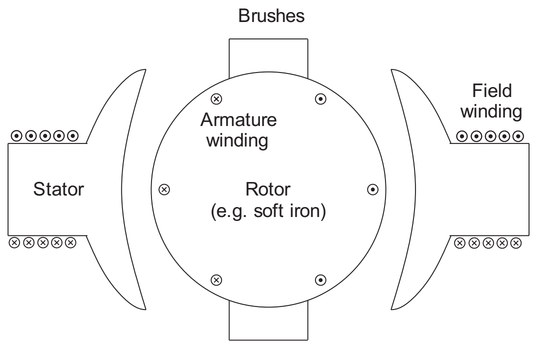


https://www.youtube.com/watch?v=LAtPHANEfQo

Basic structure of DC motor

- Direct Current (DC) motor converts electrical energy into mechanical energy.
- DC motors have two main circuits: armature (rotor) and field (stator).
- When electric current passes through a coil in an magnetic field, the magnetic force produces a torque which turns the DC motor.
- This armature circuit is supplied from an external voltage supply connected through brushes at commutators placed along the ideal magnetic neutral axis. This ideal axis is located at the mid-point between the stator field poles and is perpendicular to the field flux.
- The field winding is supplied from a DC voltage source (which may or may not be the same source as the armature's supply) that produces field current with which the field flux is set up. The presence of armature current in the field set by the field winding creates the driving torque that rotates the rotor.
- **Due to the rotor/armature movement, a voltage known as back EMF is induced in the armature**, as described by the Faraday's law. This back EMF somewhat affects the current flow in the armature winding. This interaction continues to happen until the electrical steady state is achieved. This briefly summarizes the torque and back EMF creation in DC motors.

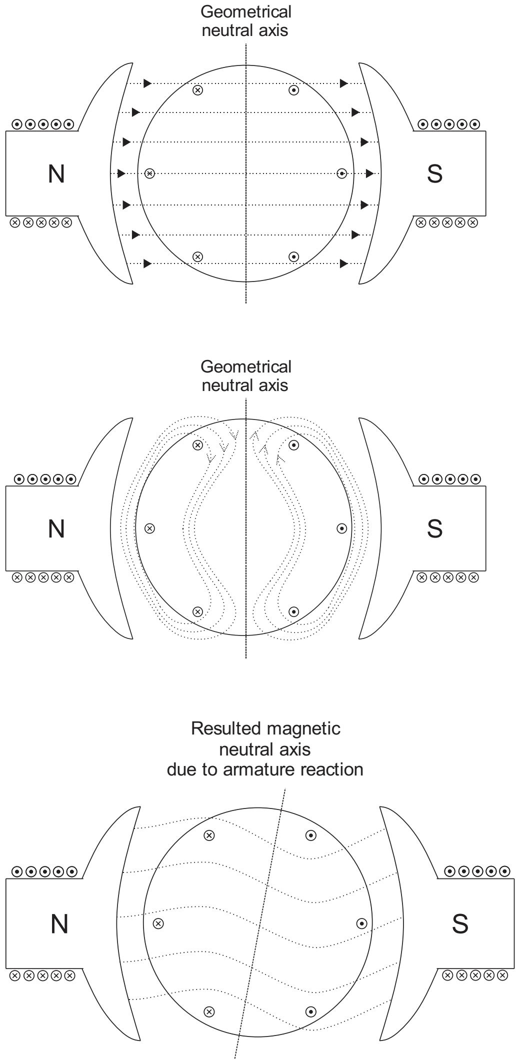


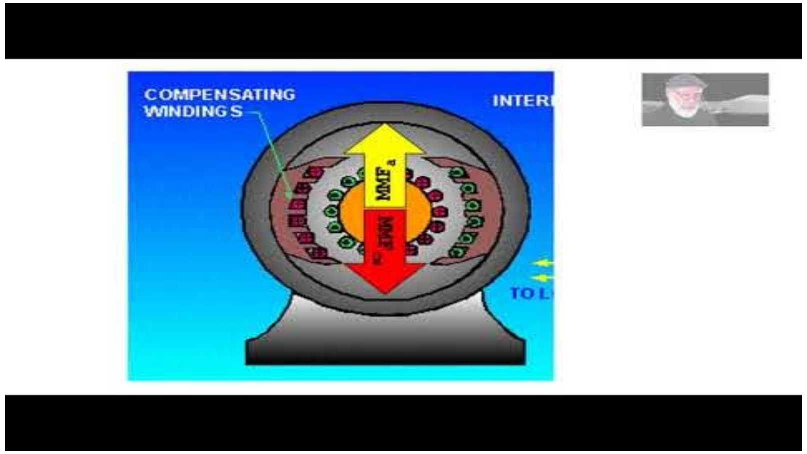


Faraday's law background info:
https://www.khanacademy.org/science/physics/magnetic-forces-and-magnetic-fields/magnetic-flux-faradays-law/v/flux-and-magnetic-flux
https://www.youtube.com/watch?v=LDOa7UdfcMQ

Armature reaction

- Armature reaction is a non-ideal phenomenon that is present in a DC motor.
- Following the Ampere’s law, the armature current also creates a magnetic field around the armature winding.
- This armature field interacts with the field flux and subsequently deviates the magnetic neutral axis from the mid-point between the stator field poles.
- This has negative consequences such as unaligned commutation which leads electric spark at the brushes (especially in DC generator) and delayed commutations.

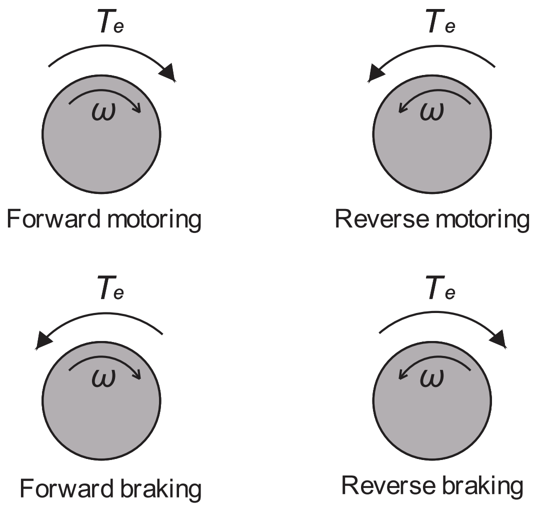


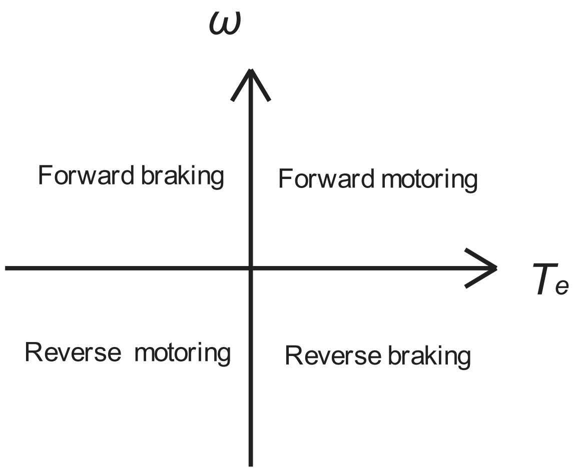


https://www.youtube.com/watch?v=zOOk6-h6tXY

Operation modes of DC motor

- There are four basic operating regions of DC machines, known as forward motoring, forward braking, reverse motoring and reverse braking.
- E.g. of forward motoring and reverse motoring are fans and pumps rotating in forward and reverse direction.
- E.g. of forward braking is a forward-moving train going downhill.
- A DC drive can operate in single-quadrant (forward or reverse motoring), two-quadrant (e.g. forward-motoring-forward-braking combination in electric vehicle, forward-motoring-reverse-braking combination in crane), or four-quadrant (train) operations.





How can speed of DC motor be controlled?

1. Flux Control Method

In the flux control method, a rheostat (a type of variable resistor) is connected in series with the field windings. The purpose of this component is to increase the series resistance in the windings which will reduce the flux, consequently increasing the motor's speed.

2. Voltage Regulation Method

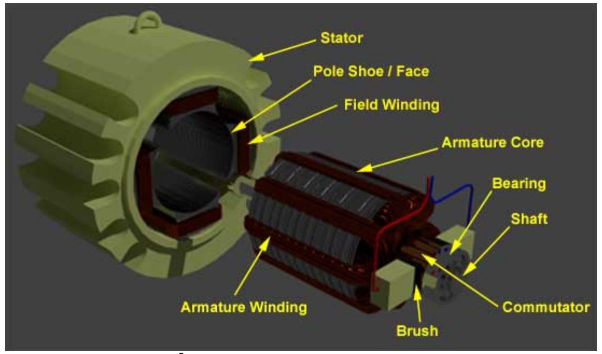
The variable regulation method is typically used in shunt dc motors. There are, again, two ways to achieve voltage regulation control:

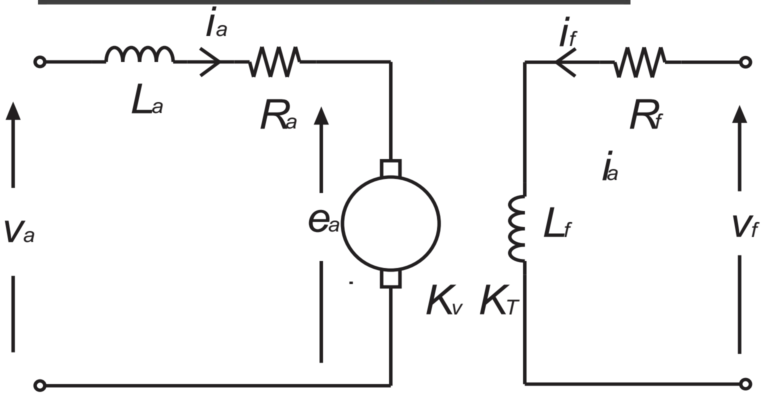
- Connecting the shunt field to a fixed exciting voltage while supplying the armature with different voltages (aka multiple voltage control)
- Varying the voltage supplied to the armature (aka the Ward Leonard method)

3. Armature Resistance Control Method

The armature resistance control is based on the principle that the speed of the motor is directly proportional to the back EMF. So, if the supply voltage and the armature resistance are kept at a constant value, the speed of the motor will be directly proportional to the armature current.

Principles of speed control of DC motor





v_a, i_a, R_a and ***L_a*** are the terminal voltage across the armature, current flows in the armature, the effective resistance and inductance of the armature winding, and e_a is the back-EMF

V_f, i_f, R_f and ***L_f*** are the terminal voltage across the field winding, current flows in the field, the effective resistance and inductance of the field winding.

- Voltage balanced equation at the field circuit:

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

- Voltage balanced equation at the armature circuit:

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_a$$

- The induced back-EMF and the developed torque are:

Back-EMF	$e_a = K_v \omega \phi_f$	The back EMF **constant**, k_v, represents the relationship between the **motor's** back EMF and its speed
Developed torque	$T_e = K_T i_a \phi_f$	The **torque constant**, k_T, is specific to **motor's** design, including its magnetic strength, number of wire turns, and armature length. The slope of the **motor's torque**-current curve is determined by the **torque constant**.

Where $\boldsymbol{\omega}$, $\boldsymbol{K_v}$ and $\boldsymbol{K_T}$ are the operating speed, voltage constant and torque constant [unit Nm/Wb/A or V.s/rad/Wb] ϕ_f is the stator magnetic flux.

Principles of speed control of DC motor, ctd.

- The basic torque balance equation that governs the speed dynamic:

$$T_e = j\frac{d\omega}{dt} + B\omega + T_L$$ where J, B, and T_L are the total inertia connected to the motor rotor shaft, the viscous friction coefficient and load torque

- For analysis purpose or if one only deals with open-loop control, the following can be assumed: given a DC motor under electrical steady state, all time-derivative terms will be nullified:

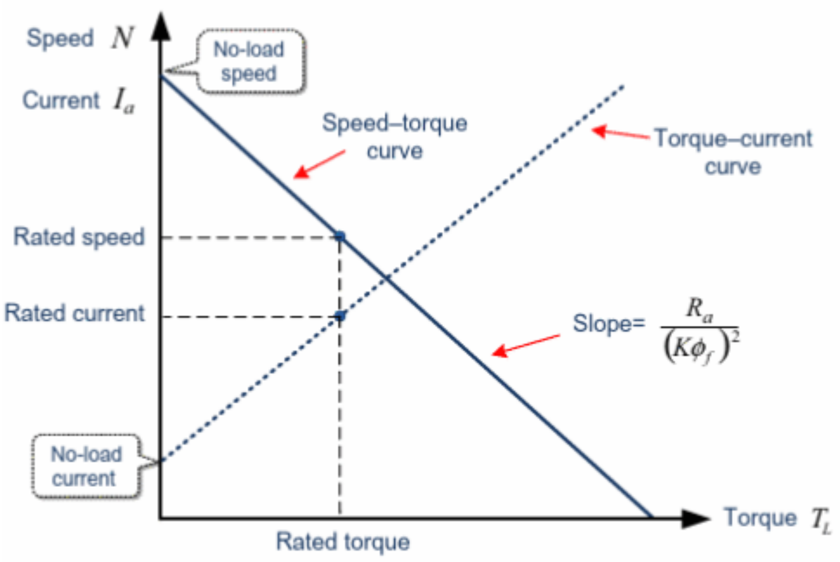
Notice that all the small capital voltage and current terms (i.e. instantaneous values) have now been replaced by block capitals, which represent steady-state values.

$$v_a = R_a i_a + L_a\frac{di_a}{dt} + e_a$$

$$T_e = j\frac{d\omega}{dt} + B\omega + T_L$$

B is the friction coefficient of the motor

$$E_a = K_v\omega\phi_f$$
$$V_a = R_a I_a + E_a = R_a I_a + K_v\omega\phi_f$$
$$T_e = K_T I_a\phi_f = B\omega + T_L$$
$$T_e = T_L = K_T I_a\phi_f$$



Electric Motor Control : DC, AC, and BLDC Motors
Sang-Hoon Kim

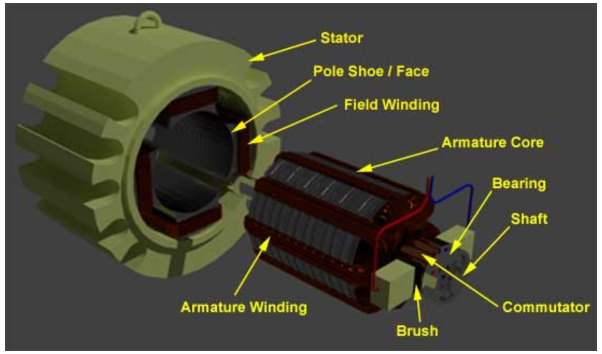
- The steady-state motor speed can be derived from:

$$\omega = \frac{V_a - R_a I_a}{K\phi_f} = \frac{V_a}{K\phi_f} - \frac{R_a}{(K\phi_f)^\wedge 2}T_L$$

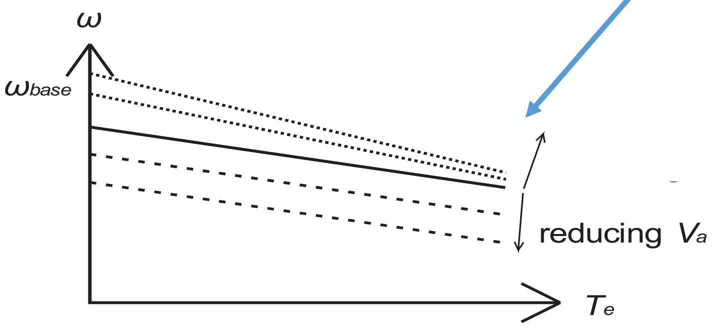
For $K_T = K_e = K$

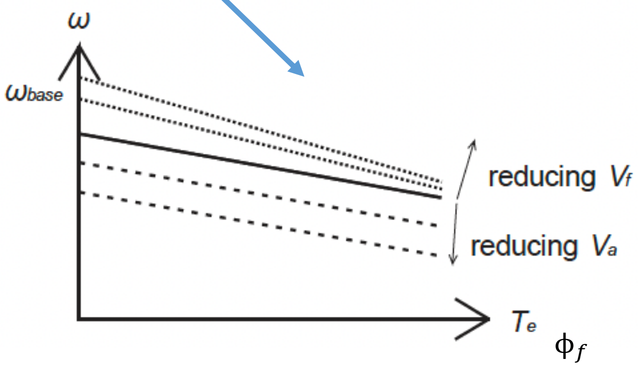
How can speed of DC motor be controlled?

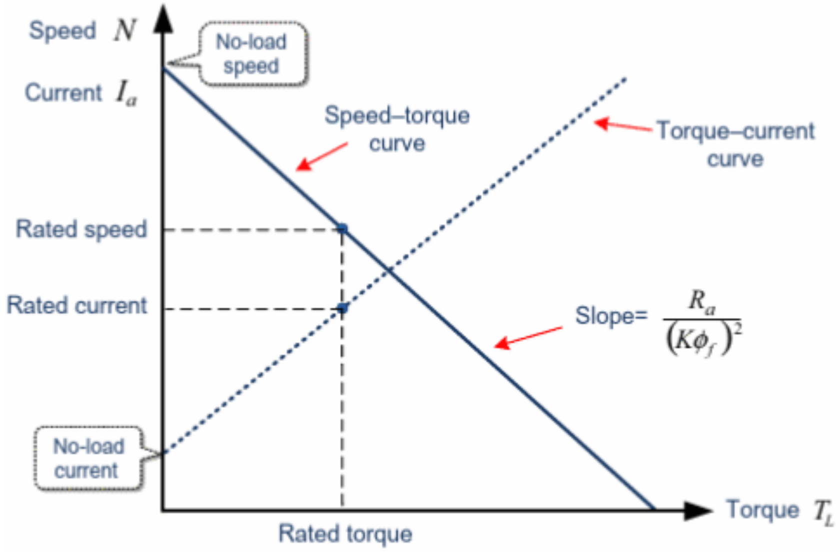
- Varying R_a (i.e. by connecting a variable resistor in series to the armature winding) is a conventional speed-control method which results in much higher copper losses.
- In modern drives with power electronic control, the speed regulation can be achieved by adjusting V_a or ϕ_f



$$\omega = \frac{V_a - R_a I_a}{K\phi_f} = \frac{V_a}{K\phi_f} - \frac{R_a}{(K\phi_f)^2} T_L$$





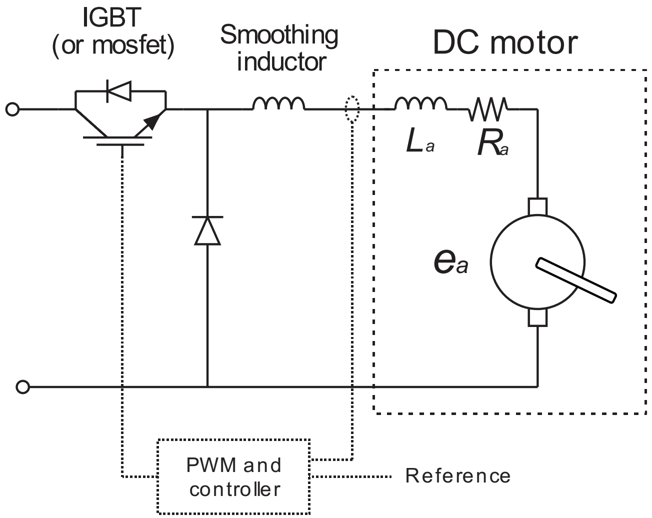


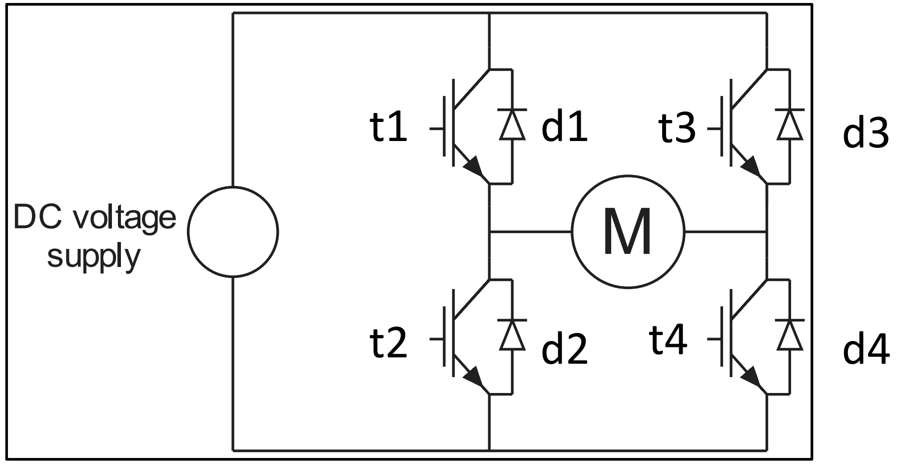
- Another parameter to be defined is the speed regulation of a DC motor, which is:

$$speed\ regulation = \frac{\omega_{no-load} - \omega_{full-load}}{\omega_{full-load}} \times 100\%$$

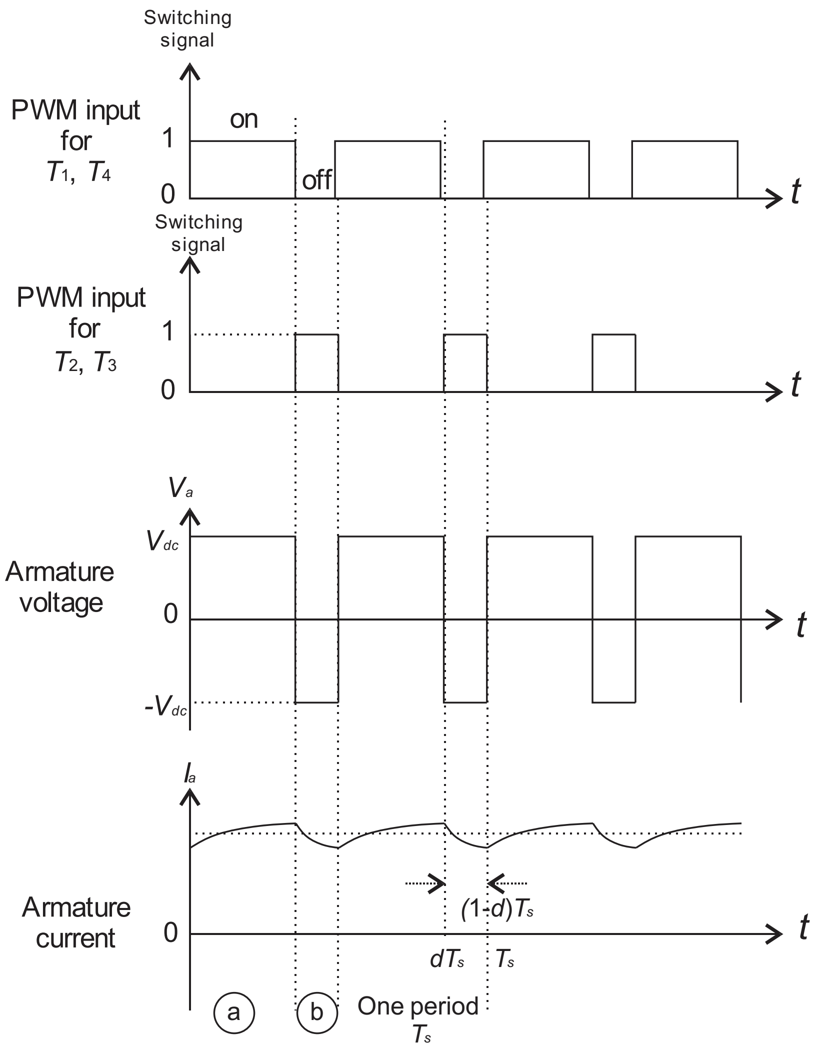
Chopper control of DC motor

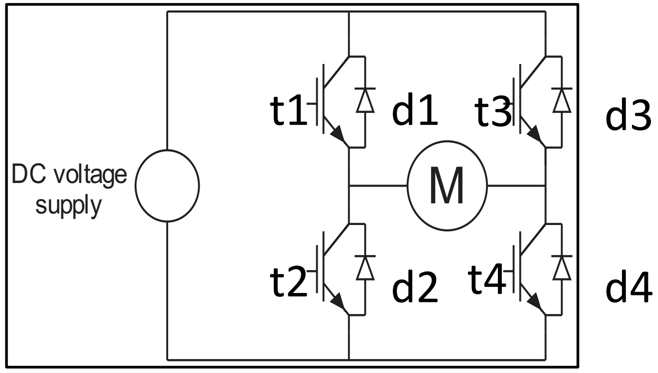
- In rectifier fed DC drives based on thyristors, the firing angle and hence the armature voltage can be altered only twice in a cycle of the input voltage (i.e. 10 ms for 50Hz AC supply). This limits the achievable dynamic response. Moreover, the machine losses become higher due to the presence of significant low order harmonics in the armature voltage and current waveforms.
- DC chopper commonly refers to the power electronic converter with PWM-operated switches such as MOSFET or IGBT. These choppers generally have higher efficiency compared to the thyristor counterparts.





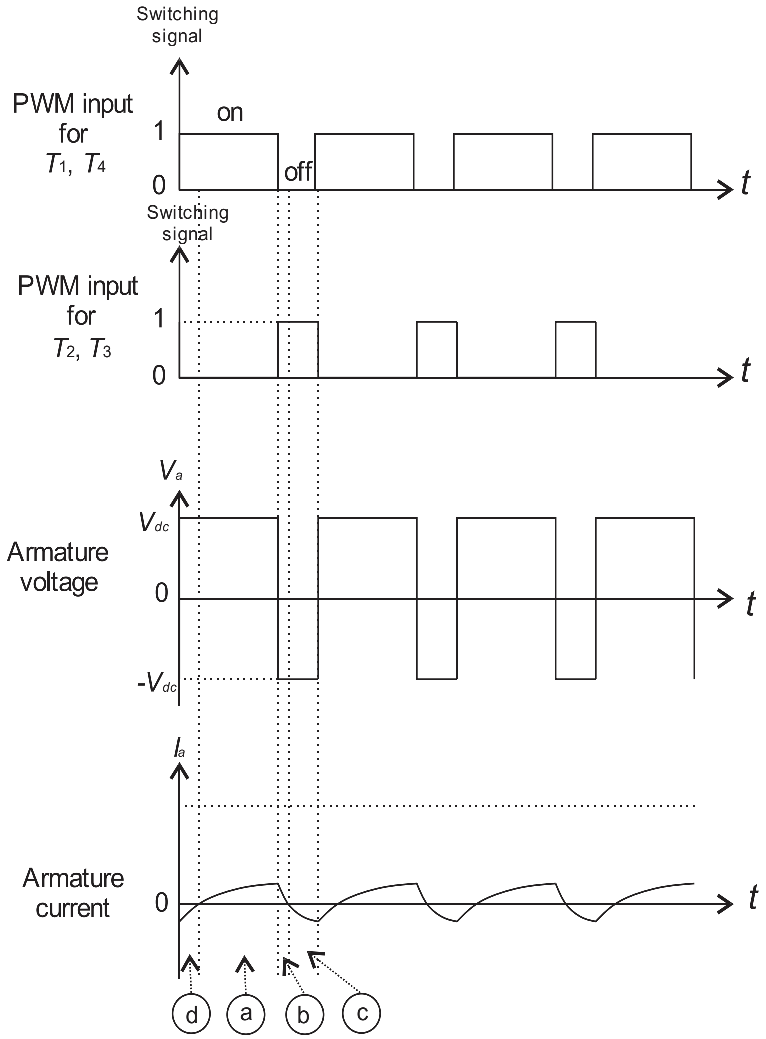
Continuous conduction mode

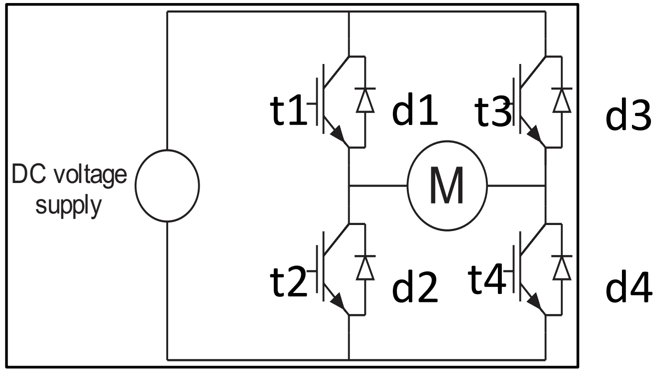




- In the continuous conduction mode, within each of the switching period, there are two operational sub-cycles:
  - T1 and T4 are turned on, and the armature current flows in the positive direction;
  - T2 and T3 are turned on but not conducting. Instead, freewheeling diodes D2 and D3 are latched on, and the armature current flows in the positive direction;
- The same applies to negative armature current.

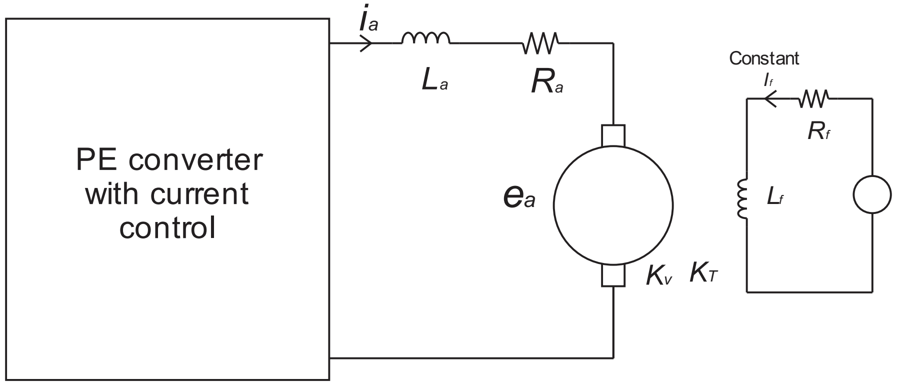
Discontinuous conduction mode





- In the discontinuous conduction mode, within each of the switching period, there are four operational sub-cycles:
  - T1 and T4 are turned on, and the armature current flows in the positive direction;
  - T2 and T3 are turned on but not conducting. Instead, freewheeling diodes D2 and D3 are latched on, and the armature current flows in the positive direction;
  - T2 and T3 are turned on and conducting, and the armature flows in the negative direction;
  - T1 and T4 are turned on but not conducting. Instead, freewheeling diodes D1 and D4 are latched on, and the armature current flows in the negative direction;

Regenerative braking of a DC motor

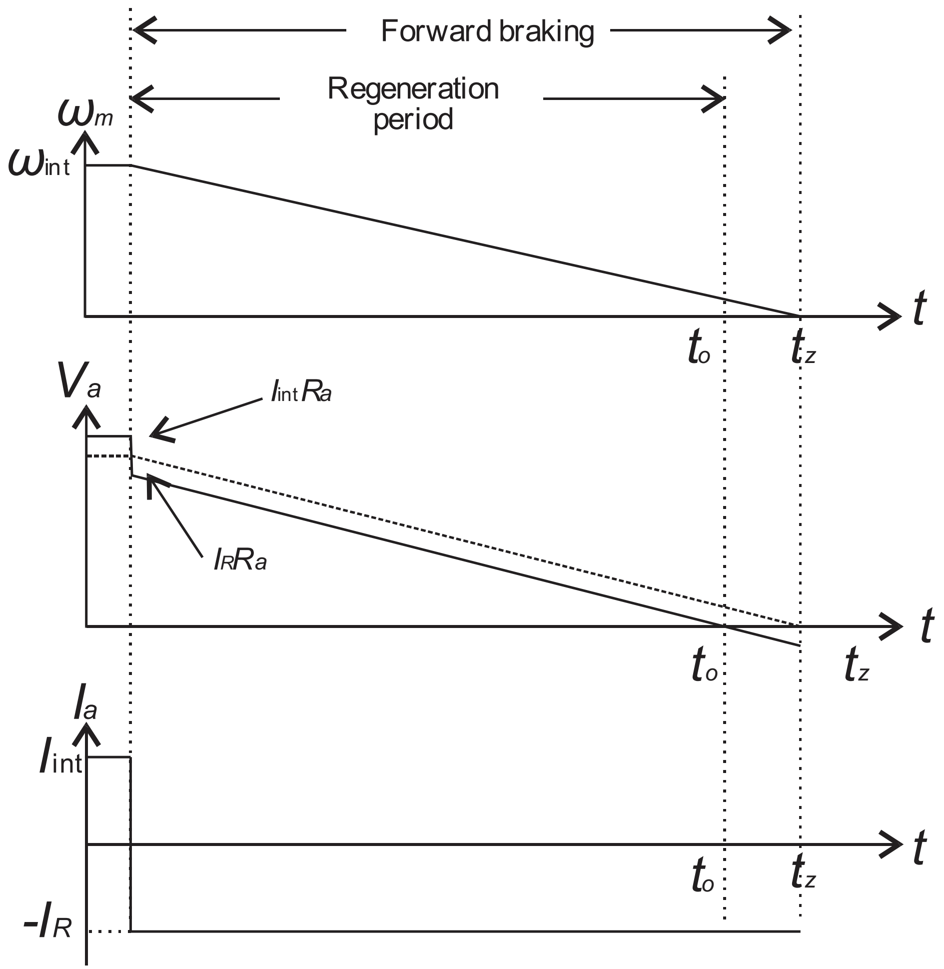


$$v_m = K_e\omega_m + i_aR_a + L_a\frac{di_a}{dt}$$
$$T = K_ti_a$$
$$T = J\frac{d\omega_m}{dt} + B\omega_m$$

where
ω_m is the speed of rotation, in rad/s;
$K_e = K_V$ is the motor's speed constant, in V/(rad/s); K_t is the motor torque constant, in Nm/A;
(We assume K_e and K_t already take into account the flux ϕ_f as per Unit definition above)
L_a is the armature inductance, in H;
T is the electromagnetic torque, in Nm.

- During regenerative braking, the kinetic energy from the rotational motion of the rotor is recaptured by the power-electronic converter.
- In order to realize generative braking, an active current control at the voltage terminal is required. This allows the assumption of constant regenerative current (hence $di_a/dt = 0$) to be made and thus simplifies the derivation.

Regenerative braking of a DC motor



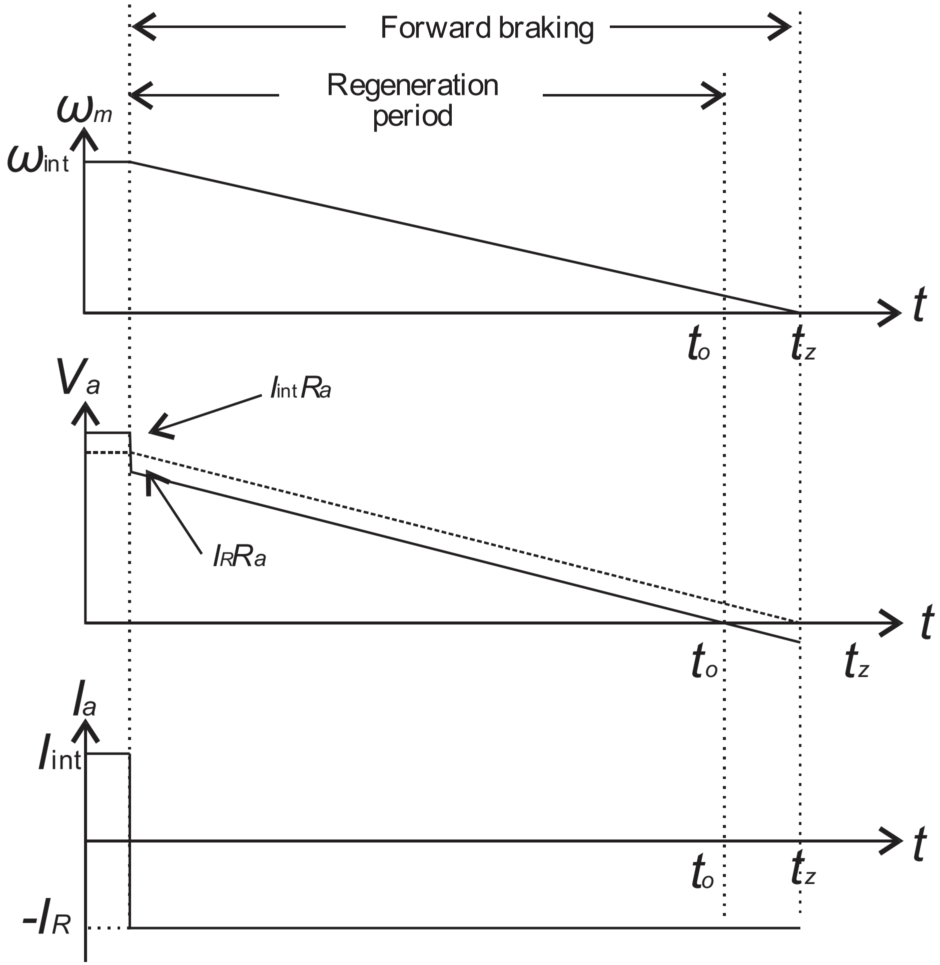
- The braking current is controlled by the DC drive to remain constant I_R (negative) during the braking period, therefore the voltage balanced equation is simplified to:

$$V_m(t) = K_e\omega_m(t) + I_aR_a + 0$$

- Assume that the windage friction is zero, no load is connected, and with constant braking armature current, the braking torque therefore remain constant too during the braking period. The deceleration is therefore a constant and the speed profile is a straight line

$$\omega_m(t) = \left(1 - \frac{t}{t_z}\right)\omega_{\text{int}}$$

Regenerative braking of a DC motor



- Braking torque developed during the deceleration/regeneration (assume no load and no windage friction):

$$T_{braking} = K_t I_R = J\alpha$$

$$\alpha = \frac{K_t I_R}{J}$$

- Since

$$\frac{K_t I_R}{J} = \frac{-\omega_{\text{int}}}{t_z}$$

$$t_z = \frac{-J\omega_{\text{int}}}{K_t I_R}$$

- From the relationship between t_o and t_z:

$$t_o = t_z\left(1 + \frac{I_R R_a}{K_e \omega_{\text{int}}}\right) \qquad t_o = \frac{-J\omega_{\text{int}}}{K_t I_R}\left(1 + \frac{I_R R_a}{K_e \omega_{\text{int}}}\right)$$

- Lastly, the regenerated energy is: $E_{regen} = \int_0^{t_o} V_m(t) I_R \cdot dt$

$$E_{regen} = \int_0^{t_o}\left[-\frac{K_e\omega_{\text{int}} t}{t_z} + K_e\omega_{\text{int}} + I_R R_a\right] I_R \cdot dt$$

$$= t_o\left[\frac{K_e\omega_{\text{int}} I_R}{2} + \frac{I_R^2 R_a}{2}\right]$$

Regenerative braking of a DC motor

$$E_{regen} = \int_0^{t_o} \left[-\frac{K_e \omega_{int} t}{t_z} + K_e \omega_{int} + I_R R_a \right] I_R \cdot dt$$

$$\frac{t_o}{\left(1 + \frac{I_R R_a}{K_e \omega_{int}}\right)} = t_z$$

$$T_{braking} = K_t I_R = J\alpha$$

$$\alpha = \frac{K_t I_R}{J}$$

$$\frac{K_t I_R}{J} = \frac{-\omega_{\text{int}}}{t_z}$$

$$t_z = \frac{-J\omega_{\text{int}}}{K_t I_R}$$

$$E_{regen} = \int_0^{t_o} \left[-\frac{K_e \omega_{int} \left(\frac{K_e \omega_{int}}{K_e \omega_{int}} + \frac{I_R R_a}{K_e \omega_{int}}\right) t}{t_o} + K_e \omega_{int} + I_R R_a \right] I_R \cdot dt$$

$$E_{regen} = \left[-I_R \frac{K_e \omega_{int} \left(\frac{K_e \omega_{int}}{K_e \omega_{int}} + \frac{I_R R_a}{K_e \omega_{int}}\right) t^2}{2 t_o} + I_R K_e \omega_{int} t + {I_R}^2 R_a t \right]_0^{t_o}$$

$$t_o = \frac{-J\omega_{\text{int}}}{K_t I_R} \left(1 + \frac{I_R R_a}{K_e \omega_{\text{int}}} \right)$$

$$E_{regen} = \int_0^{t_o} V_m(t) I_R \cdot dt$$

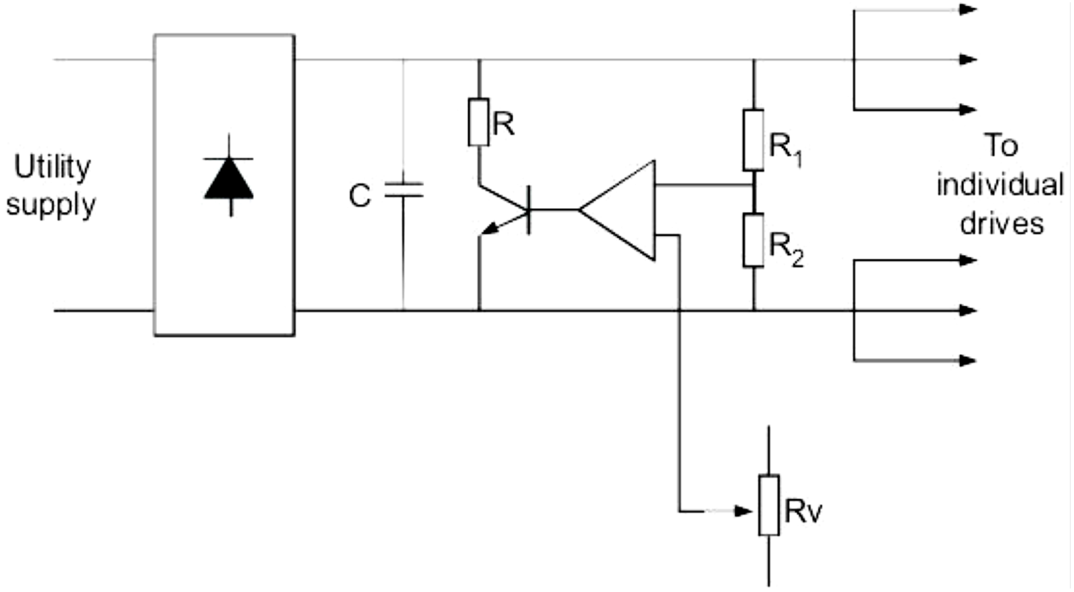
Regenerative braking of a DC motor

$$E_{regen} = \left[-I_R \frac{K_e \omega_{int} (\frac{K_e \omega_{int}}{K_e \omega_{int}} + \frac{I_R R a}{K_e \omega_{int}}) {t_o}^2}{2 t_o} + I_R K_e \omega_{int} t_o + {I_R}^2 R_a t_o \right]$$

$$E_{regen} = \left[-I_R \frac{K_e \omega_{int} t_o + I_R R_a t_o}{2} + I_R K_e \omega_{int} t_o + {I_R}^2 R_a t_o \right]$$

$$E_{regen} = t_o \left[\frac{K_e \omega_{int} I_R}{2} + \frac{I_R^2 R_a}{2} \right]$$

Capacitor approach



- During sustained regeneration, energy is dumped to the supply causing the capacitor voltage to increase. The approximate size of the capacitor to ensure the maximum bus voltage Vmax is restricted to a value below the main power bridge is given by:

$$C \geq \left| \frac{-2E_R}{V_{max}^2 - V_{min}^2} \right|$$

where Vmin is the normal bridge input voltage under steady state conditions.