Mechatronics Systems Design Laboratory

ECE 491

Igor Paprotny

Upcoming Checkout

- This week: - soldering lab (lab 1)
- Next week:
  - FRDM-KL25Z lab 2 (GPIO and ADC)
  - Altium Tutorial (Lab 3)
- BB up
- Project proposal due next Friday (project proposal guidelines on BB soon)

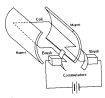
DC Motors and Motor Controllers

- DC Motors
- FET review
- Motor controllers

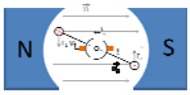
DC Motors

- Use to provide a torque to a shaft, capable of spinning the shaft to some velocity under the application of a DC current

http://www.electricalelu.com/permanent-magnet-dc-motor-or-pmdc-motor/



http://mechatronics.mech.northwestern.edu/design_ref/actuators/motor_theory.html



$$\vec{F} = i\vec{l} \times \vec{B}$$

$$\tau = \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2$$

DC Motors

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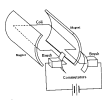

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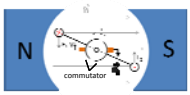

$$\vec{F} = i\vec{l} \times \vec{B}$$

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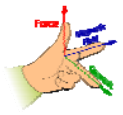
Lorenz Law

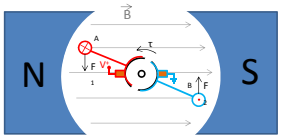
Fleming's left-hand rule for motors

- Left index finger is pointing in the direction of the magnetic field vector
- Left middle finger points in the direction of the current vector
- Thumb indicates the direction of the force

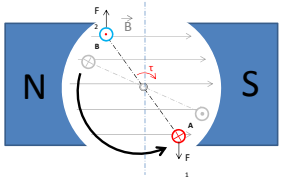


http://www.bigshotcamera.com/funbuilddables/motor401

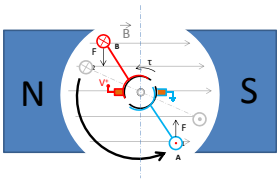
DC Motors: commutator



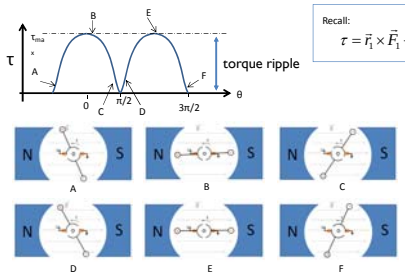
DC Motors: commutator



DC Motors: commutator



DC Motors: torque ripple

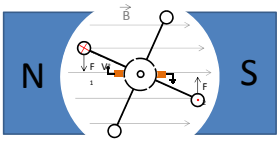


Recall:

$$\tau = \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2$$

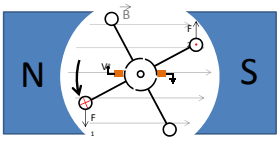
DC Motors: torque ripple

- 4-segment commutator:



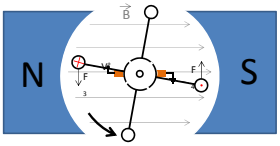
DC Motors: torque ripple

- 4-segment commutator:



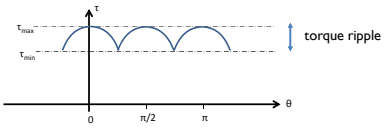
DC Motors: torque ripple

- 4-segment commutator:



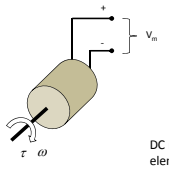
DC Motors: torque ripple

- 4-segment commutator:

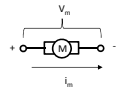


Now, greatly reduced torque ripple

Motor: Electrical Equivalent Circuit



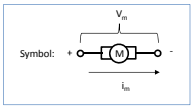
Symbol:

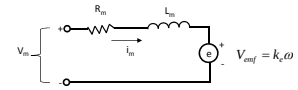


DC motor can be represented as an electrical element in a circuit diagram:

- V_m is the across element voltage (motor voltage)
- i_m is the through element current (motor current)

Motor: Electrical Equivalent Circuit





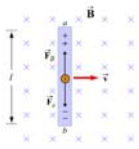
$V_{emf} = k_e \omega$

$\tau = k_t i_m$ $\quad V_m = k_e \omega + i_m R_m$ $\longleftarrow$ Assumes $\frac{di_m}{dt} \approx 0$

An equivalent circuit can be constructed to model the operation of the motor from an electrical perspective.

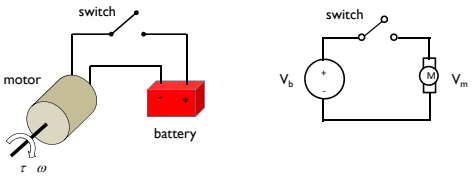
Electromotive Force in a Wire moving through B-field

Electrons in a w A wire moving through a magnetic field B at a velocity v will be pushed towards one end, while the holes will be pushed to the other end, causing a net potential V_{emf}



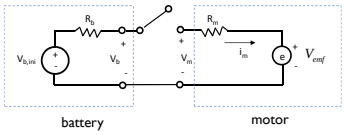
http://web.mit.edu/8.02t/www/materials/StudyGuide/guide10.pdf

Motor: Electrical Equivalent Circuit



The DC motor connected to the battery with a switch in between.

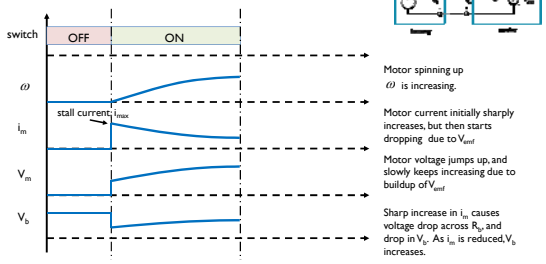
Motor: Electrical Equivalent Circuit



Combined equivalent circuit diagram for the simple battery – motor system.

Motor: Electrical Equivalent Circuit Analysis

Motor: Electrical Equivalent Circuit Analysis



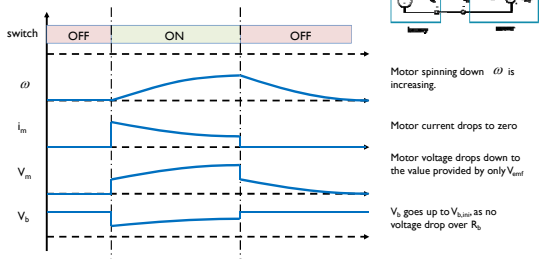
Motor spinning up ω is increasing.

Motor current initially sharply increases, but then starts dropping due to V_{emf}

Motor voltage jumps up, and slowly keeps increasing due to buildup of V_{emf}

Sharp increase in i_m causes voltage drop across R_b, and drop in V_b. As i_m is reduced, V_b increases.

Motor: Electrical Equivalent Circuit Analysis



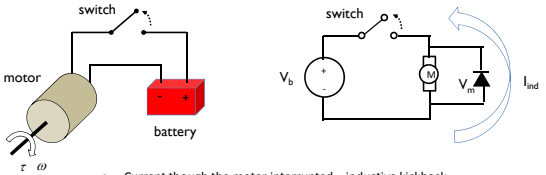
Motor spinning down ω is increasing.

Motor current drops to zero

Motor voltage drops down to the value provided by only V_{emf}

V_b goes up to $V_{b,max}$ as no voltage drop over R_b

Motor: Inductive Kickback

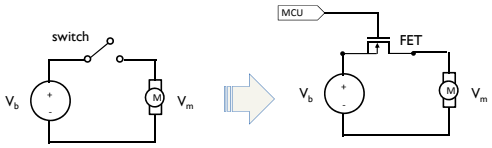


- Current though the motor interrupted – inductive kickback
- Reversed-biased snubber diodes short the resulting voltage spike

Summary: DC Motors

- DC Motors provide actuation for many mechatronic systems such as electric cars
- A commutator ensures that the torque spins the shaft in one direction for a certain polarity
- Back EMF generates a voltage across the winding, limiting the motor current, as a function of the angular velocity of the shaft (and winding)
- Two important implications of back EMF:
  - It will limit the ultimate angular velocity of the shaft (if it didn't all unloaded DC motors would likely disintegrate: $\omega \rightarrow \infty$)
  - Can be used for velocity sensing
  - Highest motor current at stall ($\omega = 0$). Motor controllers *must* be designed to handle stall currents
- Snubber diodes help to remove voltage spikes due to switching current through the winding

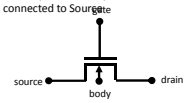
Motor Controllers



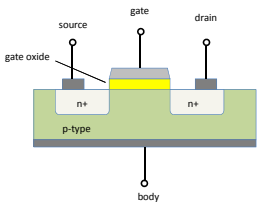
- Motor controller is an amplifier which converts the weak signals from microcontroller GPIO ports to high current that drive the motor.
- Solid-state using Power FET technology (e.g. NDP7060L)
  - Fast switching time
  - Large currents

Field Effect Transistor: A Review

- Can be n-channel or p-channel
  - Most common n-chanel
- Fabricated on a doped silicon substrate
- Has four terminals: Source, Drain, Gate, and Body.
  - If not specified, body is assumed connected to Source



Symbol

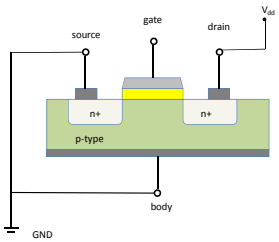


Cross-section of an n-type (n-channel) FET

Field Effect Transistor: A Review

FET Operation (n-channel)

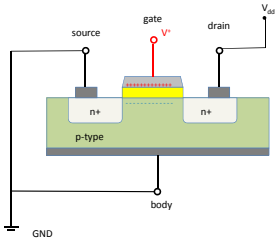
- source/body is usually connected to ground
- drain is connected to V_{dd}
- Initially source and drain isolated through a dual PN junction



Field Effect Transistor: A Review

FET Operation (n-channel)

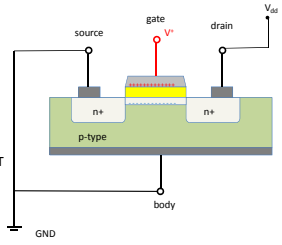
- To switch transistor on, gate is connected to positive voltage
- Accumulation of **positive** charges on the gate electrode attracts **negative** charges just underneath the gate, in the channel region



Field Effect Transistor: A Review

FET Operation (n-channel)

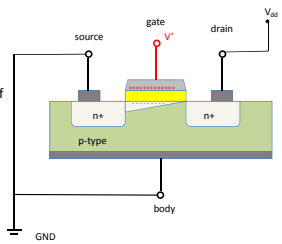
- When the density of negative charges in the channel reaches a certain threshold, the channel becomes conductive
  - Above gate threshold voltage
- Initially, channel acts like a resistor, FET operates in the **linear region**



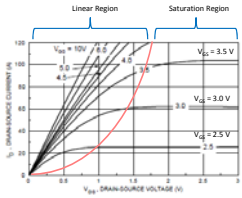
Field Effect Transistor: A Review

FET Operation (n-channel)

- As drain to source voltage (V_{ds}) increases, the channel gets pinched off at the drain, limiting the drain to source current (i_{ds})
- FET is now operating in the **saturation region**

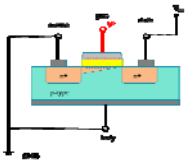


Field Effect Transistor: A Review



I/V characteristics for a NDP7060L Power FET

Datasheet NDP7060L



Summary: Field Effect Transistors

- Power FETs are used as solid state switches in a motor controller
- In an n-channel FET, positive charges on the gate form a n-type channel between the source and the drain
- Once on, a FET operates in either linear or saturated region