Mechatronics Systems Design Laboratory
ECE 491

Igor Paprotny

Upcoming Checkout

- This week:
  – FRDM-KL25Z lab 2 (GPIO and ADC)
- Next week:
  – PWM (Lab 3)
  – Altium Tutorial (Lab 4)

- BB up
- Project proposal due next Friday (project proposal guidelines on BB soon)

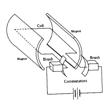
DC Motors and Motor Controllers

- DC Motors
- FET review
- Motor controllers

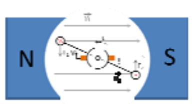
DC Motors

- 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.electrical4u.com/permanent-magnet-dc-motor-or-pmdc-motor/

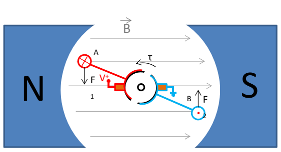


http://mechatronics.mech.northwestern.edu/design_ref/actuators/motor_theory.html

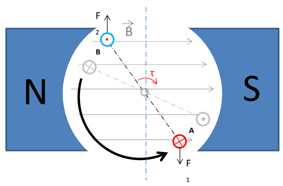


$$\vec{F} = i\vec{l} \times \vec{B}$$
$$\tau = \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2$$

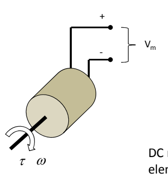
DC Motors: commutator

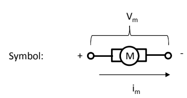


DC Motors: commutator



Motor: Electrical Equivalent Circuit

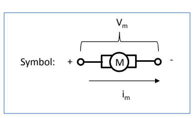


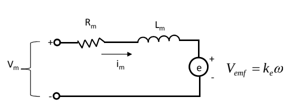


DC motor can be represented as an electrical element in a circuit diagram:

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

Motor: Electrical Equivalent Circuit





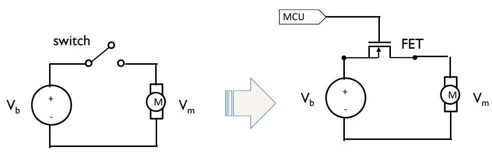
$\tau = k_t i_m$ $\quad V_m = k_e\omega + i_m R_m$ ← Assumes $\frac{di_m}{dt} \approx 0$

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

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 (ω = 0). Motor controllers *must* be designed to handle stall currents
- Snubber diodes help to remove voltage spikes due to switching current through the winding

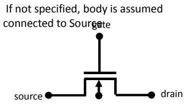
Motor Controllers



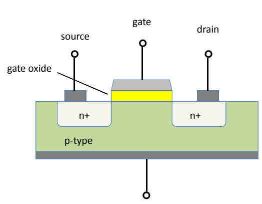
- Motor controller is an amplifier which converts the weak signals from microcontroller GPIO ports to high current that drive the motor.
- Solid-state using Power FET technology (e.g. NDP7060L)
  - Fast switching time
  - Large currents

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

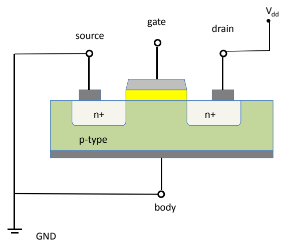


Cross-section of an n-type (n-channel) FET

Field Effect Transistor: A Review

FET Operation (n-channel)

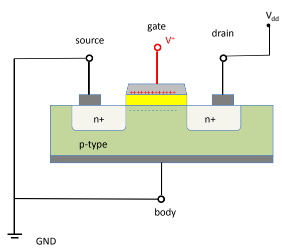
- source/body is usually connected to ground
- drain is connected to V_{dd}
- Initially source and drain isolated through a dual PN junction



Field Effect Transistor: A Review

FET Operation (n-channel)

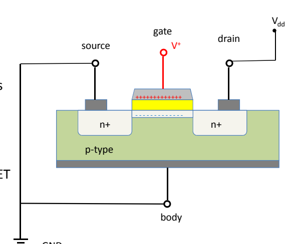
- To switch transistor on, gate is connected to positive voltage
- Accumulation of **positive** charges on the gate electrode attracts **negative** charges just underneath the gate, in the channel region



Field Effect Transistor: A Review

FET Operation (n-channel)

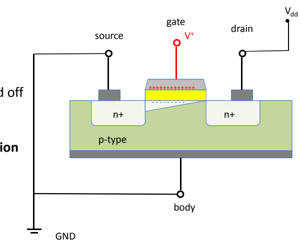
- When the density of negative charges in the channel reaches a certain threshold, the channel becomes conductive
  - Above gate threshold voltage
- Initially, channel acts like a resistor, FET operates in the **linear region**



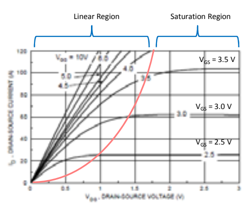
Field Effect Transistor: A Review

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**

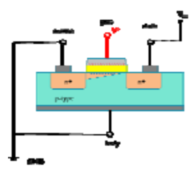


Field Effect Transistor: A Review



I/V characteristics for a NDP7060L Power FET

Datasheet NDP7060L

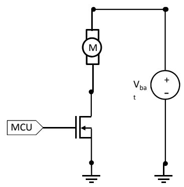


Summary: Field Effect Transistors

- 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

Motor Controllers: FETS as switches

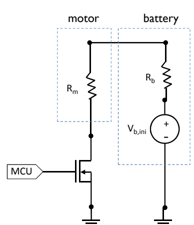
- Switch is now replaced with a FET
- Single FET motor controller
  - Only turn in one direction
- Motor and battery resistance in series
  - Analyze for maximum (i.e. stall) current



single transistor controller

Motor Controllers: FETS as switches

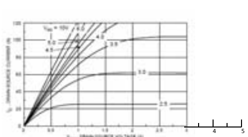
- Modify electric diagram for stall (ω = 0)
  - No back EMF
  - No inductive component
- Load-line analysis



single transistor controller

Motor Controllers: FETS as switches

- E.g. assume
  - $V_{b,ini}$ = 5 V, R_m = 0.4 Ω, R_b = 0.1 Ω
  - V_{gs} provided by the MCU



I/V characteristics for a NDP7060L Power FET

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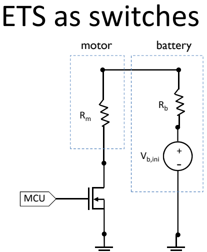

single transistor controller

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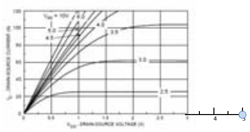

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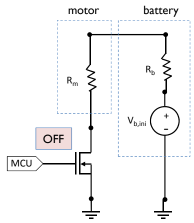
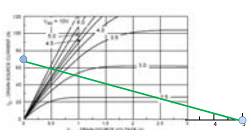


single transistor controller

Motor Controllers: FETS as switches

- E.g. assume
  - $V_{b,ini} = 5$ V, $R_m = 0.06\ \Omega$, $R_b = 0.01\ \Omega$
  - V_{gs} provided by the MCU



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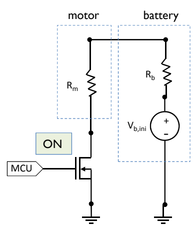

single transistor controller

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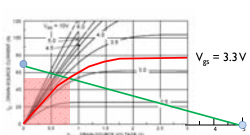

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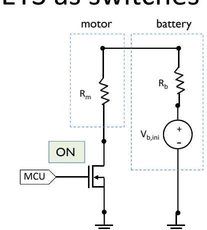

single transistor controller

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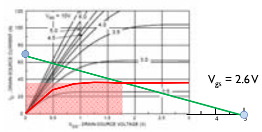

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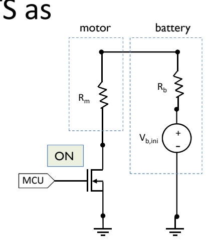
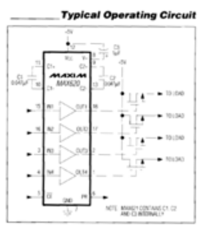


single transistor controller

Motor Controllers: the need for FET drivers

- To reduce the power dissipation in ON state, V_{gs} must be as high as possible (up to gate voltage breakdown)
  - V_{gs} may be above V_{dd}
- 3.3 V output from GPIO not high enough
- Solution: FET Drivers
  - Solid-state circuits that elevate ON output voltage to a higher ON level.
  - In some cases much higher than V_{dd}
  - E.g. MAX 621elevates ON output voltage by 11 V *above* V_{dd}.



Datasheet MAX620/621

Motor Controllers: FETS as switches

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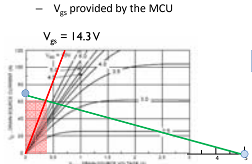
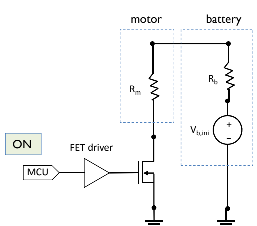


I/V characteristics for a NDP7060L Power FET

Datasheet NDP7060L



single transistor controller

Summary: Motor Controllers

- Motor controllers are used to control the actuation of a motor using one or more FETs
- Load-line analysis is used to determine power dissipated in a FET in a motor controller
- To lower dissipated power in FET, V_{gs} needs to be as high as possible
- A FET driver is used to elevate V_{gs} above V_{dd} ensuring proper switching

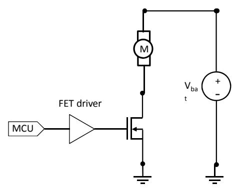
Mechatronics Systems Design Laboratory
ECE 491

Motor Control, PWM and Servo Control

- Motor controller topologies
- PWM for motor (velocity) control
- Review of servo operation
- PWM for servo (steering) control

Motor Controllers Topologies

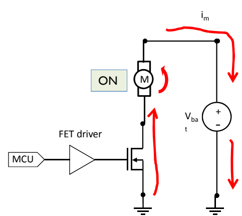
- Single FET motor controllers have the simplest topology
  - Can only accelerate, and coast to stop
- Other topologies allow for:
  - Breaking
  - Backwards motion
- Most common, full H-bridge
- Possible to use a half-bridge to simplify the controller design



single transistor controller

Motor Controllers Topology: Single FET

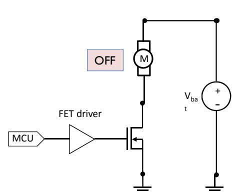
- FET ON
  - Accelerates



single transistor controller

Motor Controllers Topology: Single FET

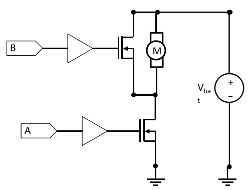
- FET OFF
  - Coasts (open connectors) to stop



single transistor controller

Motor Controllers Topology: Half-Bridge

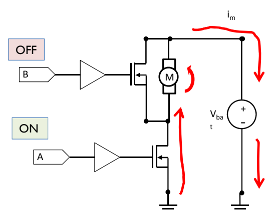
- It is possible to accelerate breaking by use the concept of **dynamic breaking**
- The V_{emf} generated by the motor is used to drive current through armature to cause breaking of the motor
- Required additional FET



Half-bridge

Motor Controllers Topology: Half-Bridge

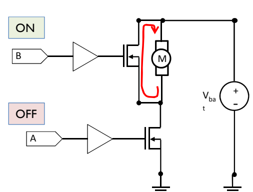
- Accelerate:
  - A ON, B OFF



Half-bridge

Motor Controllers Topology: Half-Bridge

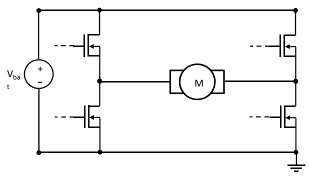
- Dynamic Breaking:
  - A OFF, B ON



Half-bridge

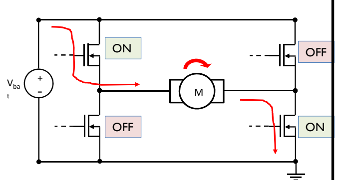
Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology is an H-bridge
- Requires four (4) FETs per motor



Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
  - Motion forward



Motor Controllers Topology – H-Bridge

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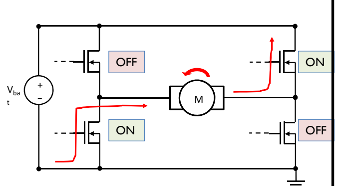
- Requires four (4) FETs per motor
- Supports:
  - Motion forward
  - Motion backward



Motor Controllers Topology – H-Bridge

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- Requires four (4) FETs per motor
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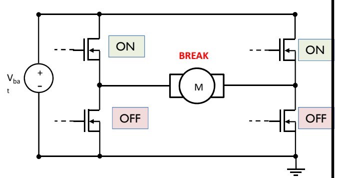
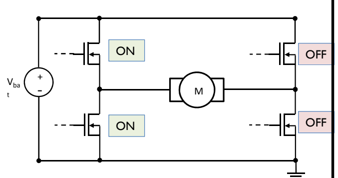
  - Breaking



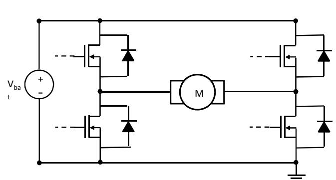
Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
  - Motion forward
  - Motion backward
  - Breaking
- Caution – H-bridge can short V_{dd} and ground



Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
  - Motion forward
  - Motion backward
  - Breaking
- Caution – H-bridge can short V_{dd} and ground
- Kick-back snubber diodes

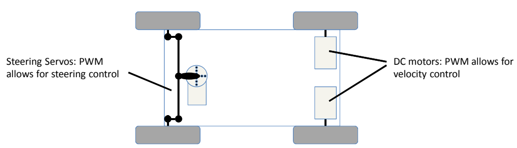


Summary: Motor Controller Topology

- Single FET controller allows for acceleration (ON) or coasting (OFF)
- Half-bridge allows for acceleration, breaking, and coasting
- The most versatile motor controller configuration is an H-bridge
- H-bridge allows for
  - Motor actuation both back and forth
  - Dynamic breaking
- Careful not to short battery terminals in H-bridge !

Control for Autonomous Car Actuation

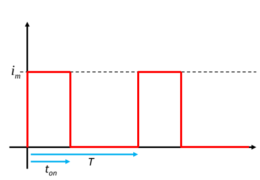
- Autonomous car contains two main actuators
  - DC Motors: provide forward propulsion
  - Servos: provide steering
- Pulse-width modulation (PWM) allows for control of both



Pulse-Width Modulation (PWM): DC Motors

Pulse-Width Modulation (PWM) is used to vary torque produced by a motor while still using a driver FET only in either completely off or completely on states.

- Alternative (Bad approach):
  - Use the FET as a variable resistor
  - Large power dissipation by the FET
- Recall that: $\tau = k_t i_m$
- *Pulse i_m by switching it fast on and off*
  - *Solid-state switch*



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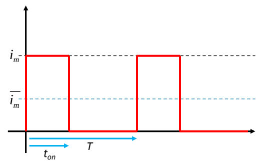
  - Large power dissipation by the FET
- Recall that: $\tau = k_t i_m$
- Duty cycle: $d = \frac{t_{on}}{T}$

$\overline{i_m} = d \cdot i_m \Rightarrow \overline{\tau} = k_t \cdot \overline{i_m}$



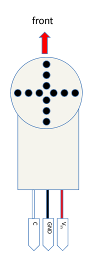
RC Servo: Introduction

- RC servos
  - Initially developed for position control in radio-controlled RC applications
  - Low precision combination of DC motor and position feedback.
  - Currently used for other than RC applications in robotics, mechatronics

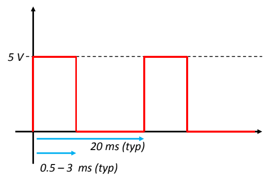
https://www.hackmeister.dk/2010/07/controlling-an-rc-servo-with-an-fpga/

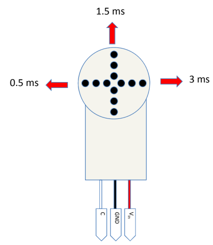
RC Servo: Control

- Servo operation:
  - Most RC servo has three wires, almost universally color coded accordingly
    - » RED – supply voltage (Vin), 5 V.
    - » BLACK – Ground (GND)
    - » WHITE – Signal (S)
- Servo can typically rotate +/- 90 deg.
- Signal (S) causes the output shaft to rotate to a set position.
  - Position encoded in a pulse train provided to S
  - Period of 20 – 30 ms (typical)
  - Pulse 0.5 – 3 ms (typical)



RC Servo: PWM





- Note: PWM in servo control different than for PWM in motors !

PWM using MCU

- Usually MCUs have ability to configure PWM for use with the GPIOs
  - Using timers to provide output PWM signal to both motors and servo
  - Independent channels per timer
    - Must be configured to assign timer and channel to a desired GPIO for output

Summary: PWM Motor and Servo Control

- Pulse-width modulation (PWM) is an efficient way of controlling power, and thus torque, of the motors
  - Can be used for velocity control
  - Avoids power drop over the FETs
  - **PWM duty-cycle** control the power
- Servos use an input pulse-train to control the direction of the output shaft
  - Can use PWM for control the direction of the servo
  - **PWM pulse duration** controls the direction
  - Must be calibrated