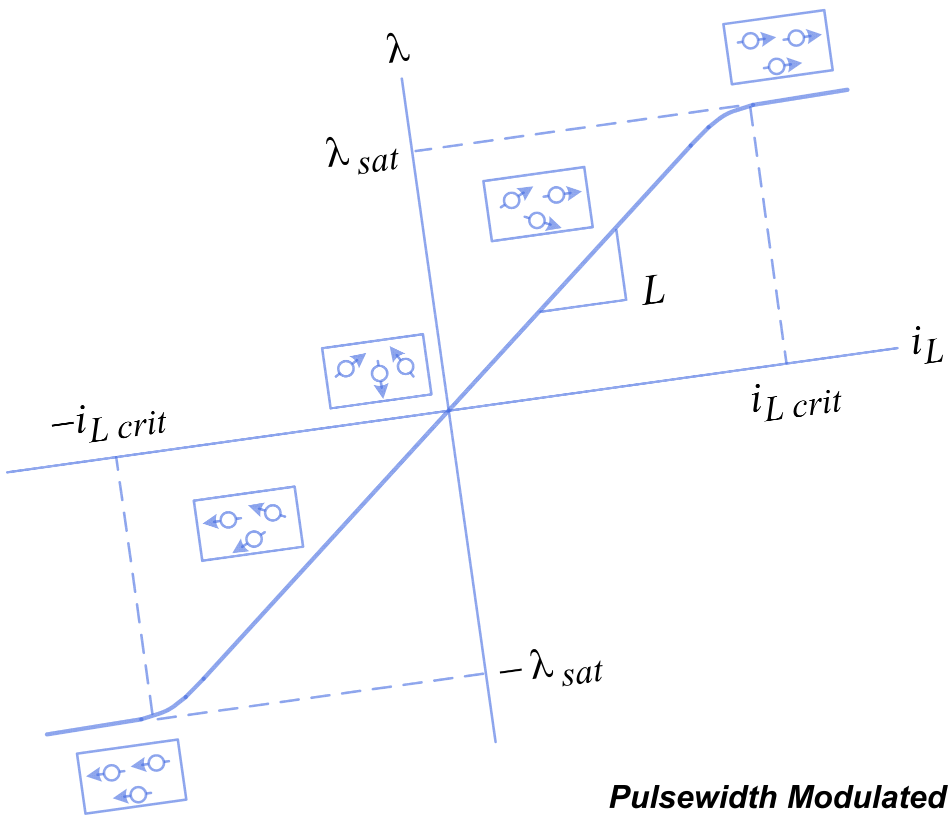
Chapter 2

Power Stage Components



Pulsewidth Modulated Dc-to-Dc Power Conversion. By Byungcho Choi

Chapter Outline

1) Semiconductor Switches

   MOSFETs

   Diodes

   MOSFET-Diode Pair as SPDT Switch

2) Energy Storage and Transfer Devices

   Inductors

   Capacitors

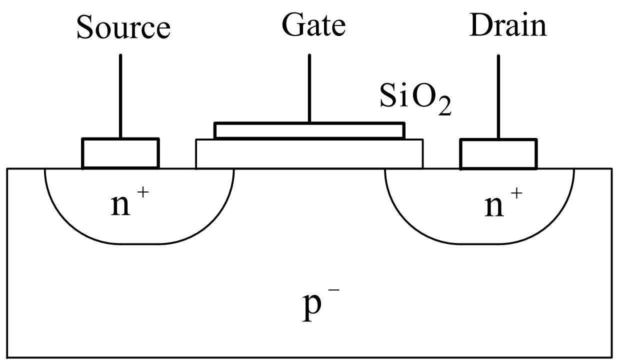
   Transformers

3) Switching Circuits in Practice

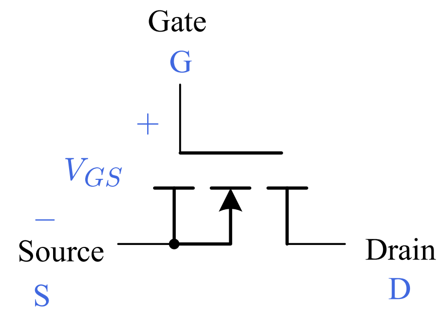
   Solenoid Drive Circuits

   Capacitor Charging Circuit

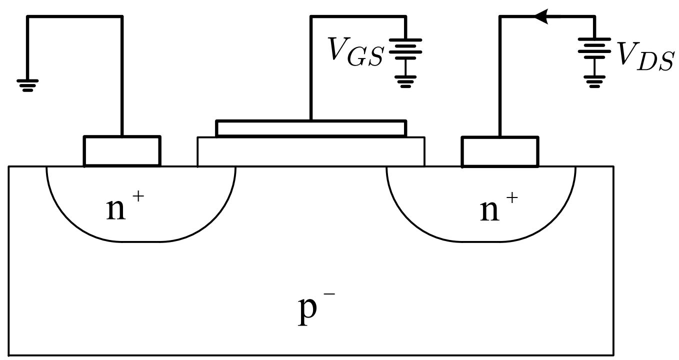
MOSFET Switching



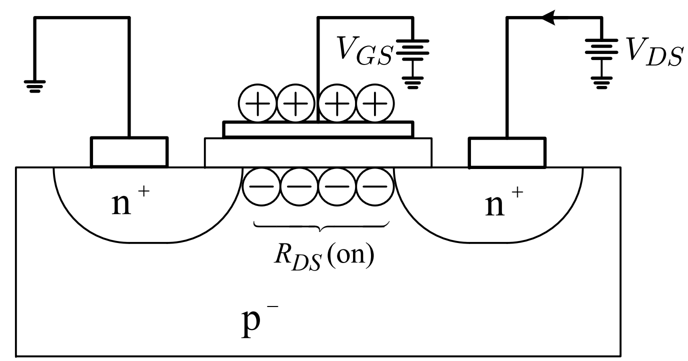
$\Rightarrow$



Off-state

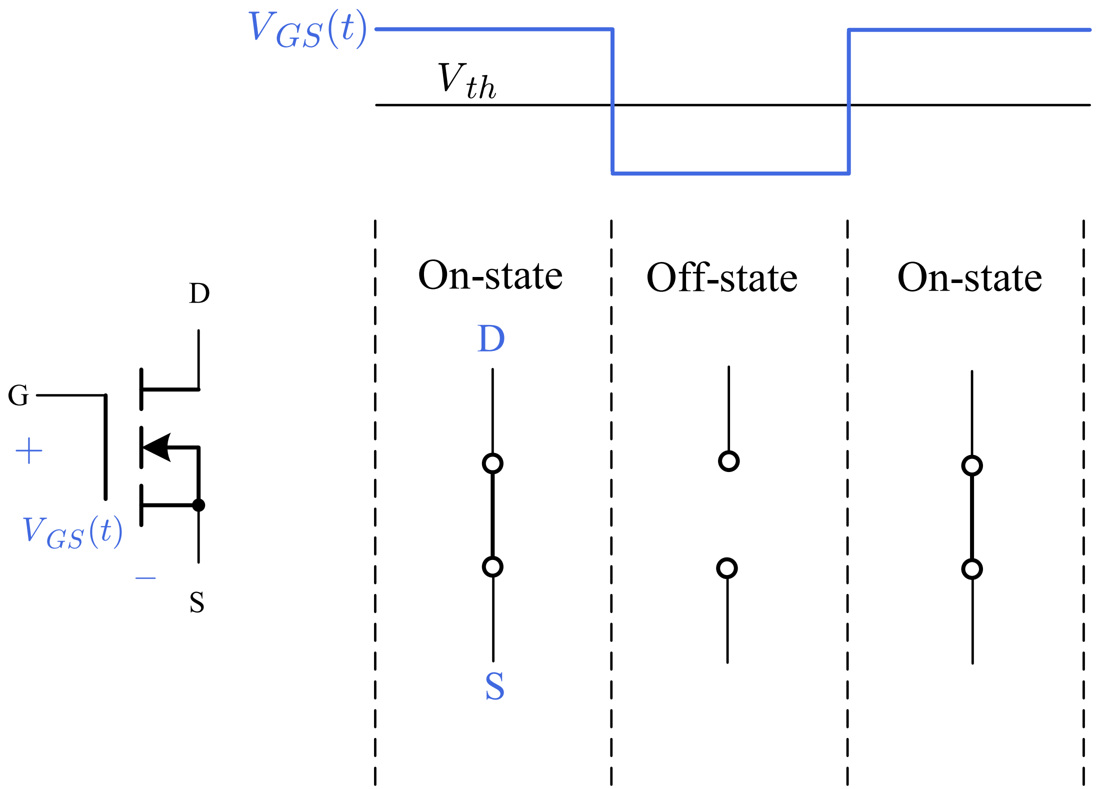


On-state



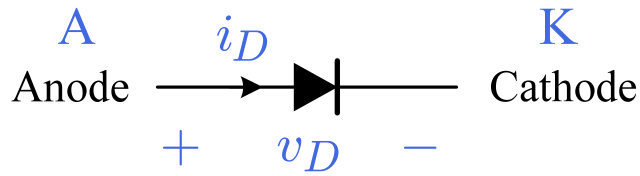
V_{th}: threshold voltage

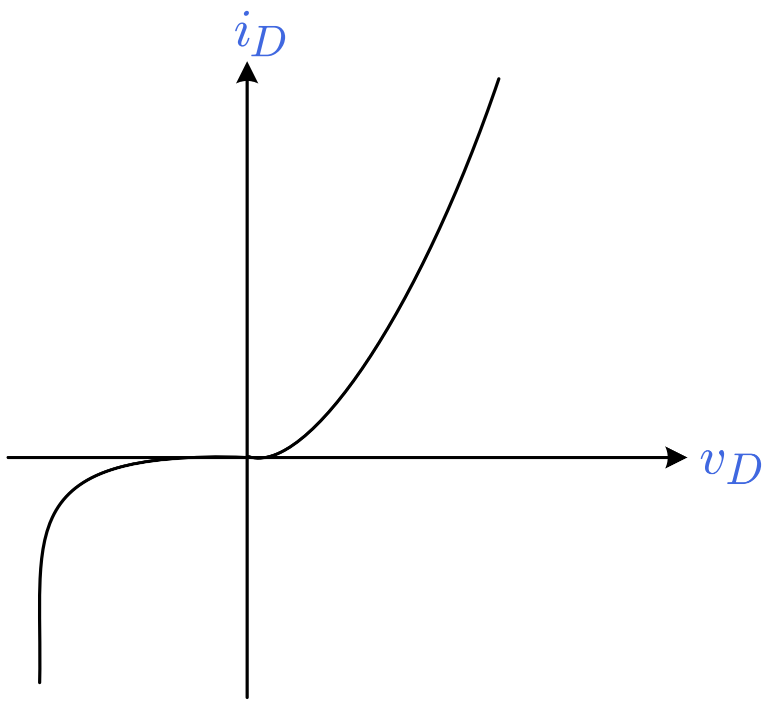
MOSFET Switching

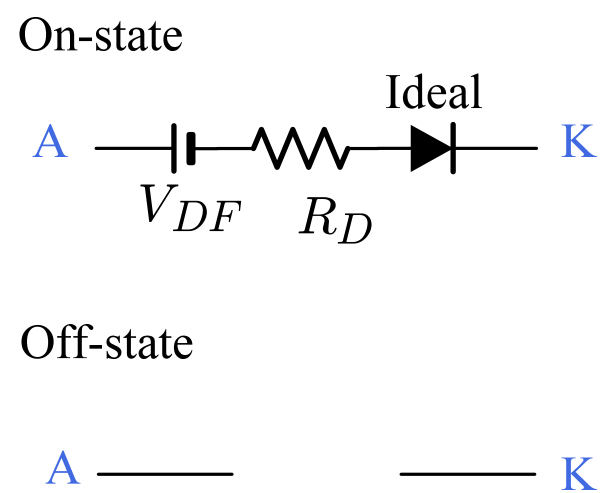


- MOSFET status is actively controlled by $v_{GS}(t)$.

Diode Modeling

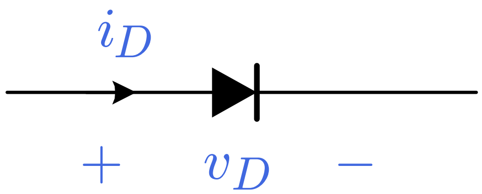






- Diode status is passively determined by the condition of application circuits.

Diode Switching



- Voltage-controlled switching

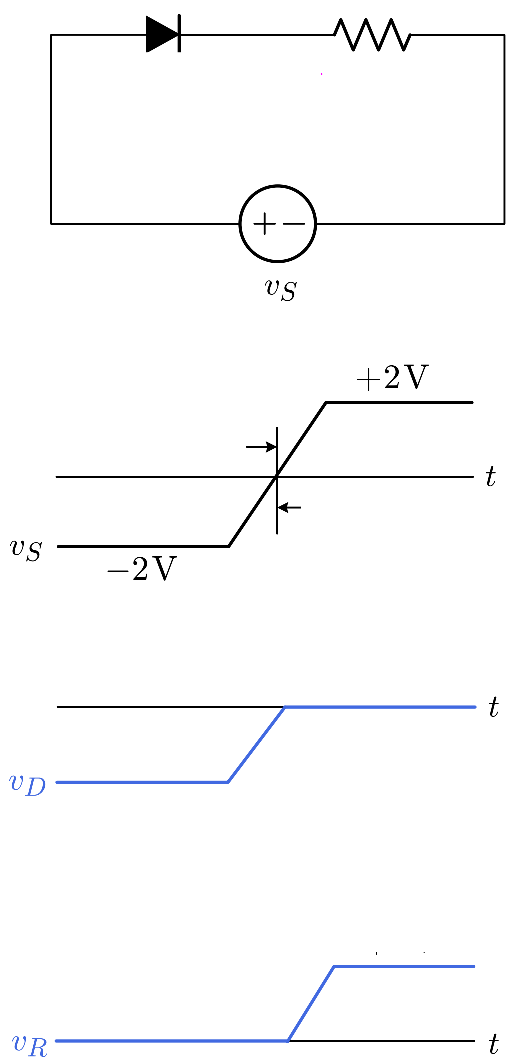
  A diode turns on when the circuit imposes a positive voltage v_D across it. Otherwise, it turns off.

- Current-controlled switching

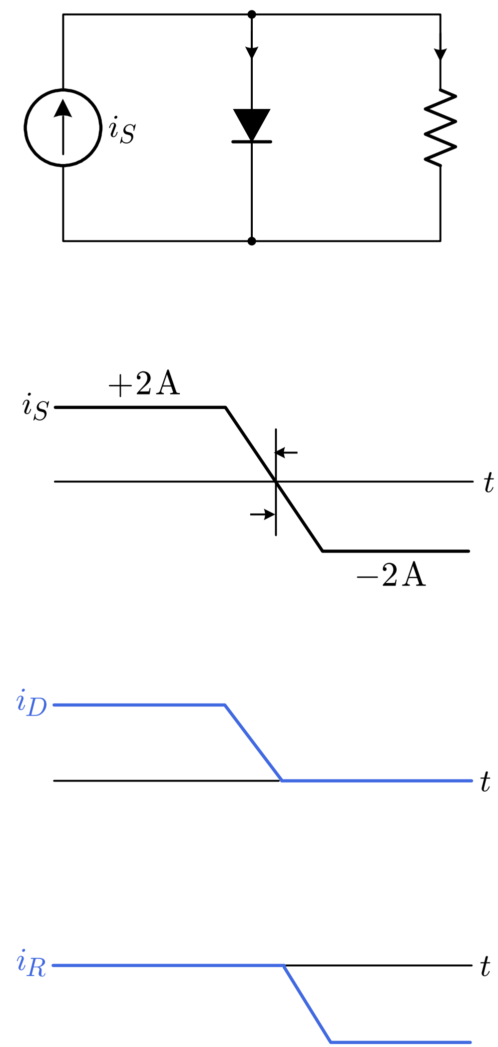
  A diode turns on when the circuit imposes a positive current i_D through it. Otherwise, it turns off.

Examples of Diode Switching

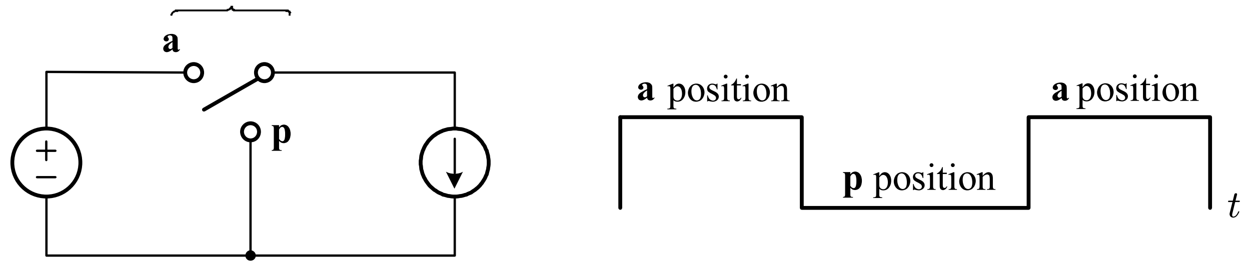
Voltage-controlled switching

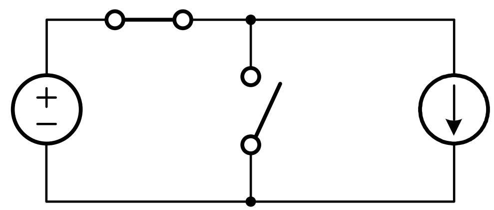


Current-controlled switching

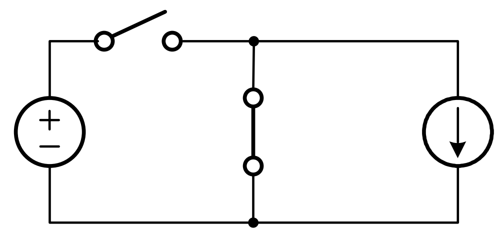


MOSFET-Diode Pair as SPDT Switch

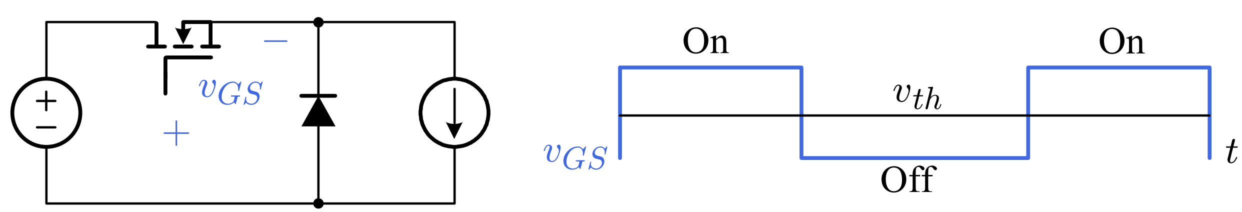




a position



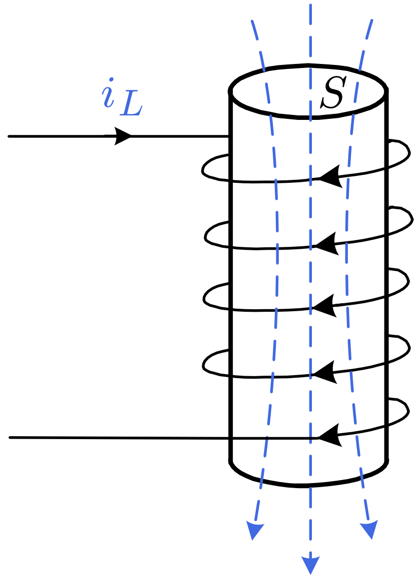
p position



MOSFET on $\Rightarrow$

MOSFET off $\Rightarrow$

Definition of Inductance

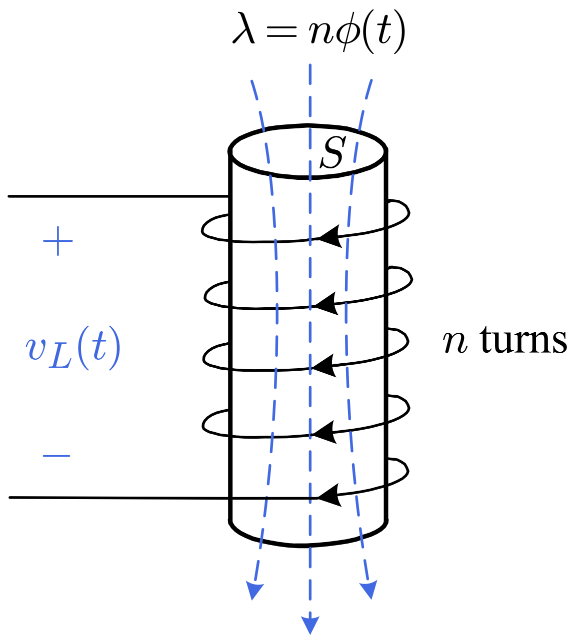


- Electro-magnetic process in inductor

$$i_L(t) \;\rightarrow\; H(t) \;\rightarrow\; B(t) = \mu H(t) \;\rightarrow\; \phi(t) = SB(t) \;\rightarrow\; \lambda(t) = n\phi(t)$$

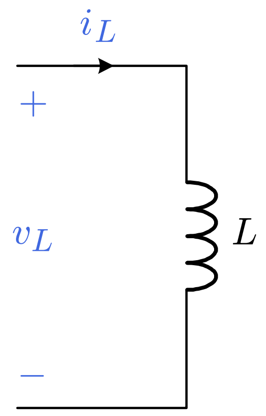
- Definition of inductance

Faraday’s Law and Circuit Equation of Inductor



- Faraday's law: time-varying magnetic flux induces a voltage across the inductor

Circuit Equations of Inductor



- Basic equations

$$i)\quad v_L(t) = \frac{\mathrm{d}\lambda(t)}{\mathrm{d}t} \qquad \Rightarrow$$

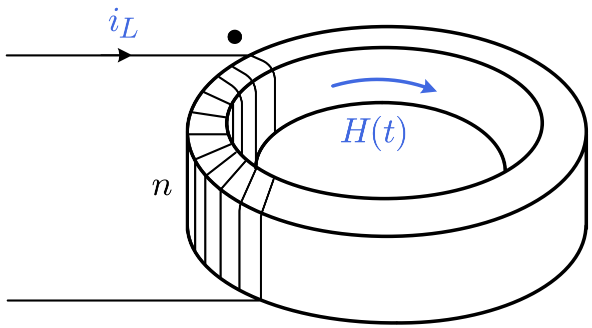
$$\left.\begin{aligned} ii)\quad v_L(t) &= \frac{\mathrm{d}\lambda(t)}{\mathrm{d}t} \\ \lambda(t) &= Li_L(t) \end{aligned}\right\} \Rightarrow$$

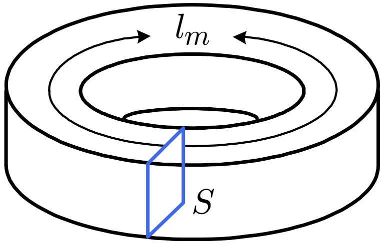
- Special cases

With $v_L(t) = V_S$,

With $i_L(t) = I_S$,

Inductance of Toroidal Inductor





- Inductance: $L \equiv \dfrac{\lambda(t)}{i_L(t)}$

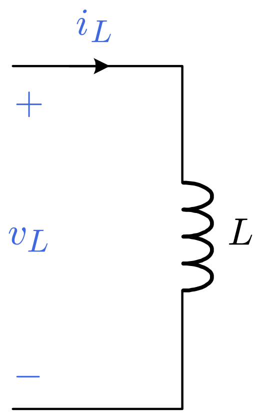
- Ampere's law

$\Rightarrow$

μ_r : relative permeability

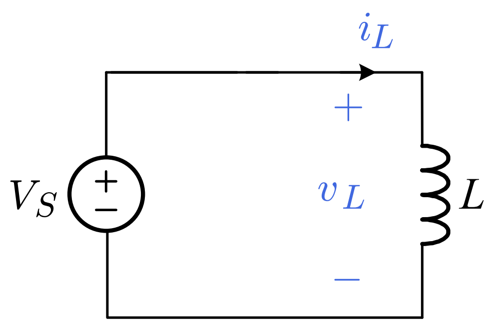
μ_o : permeability of free space

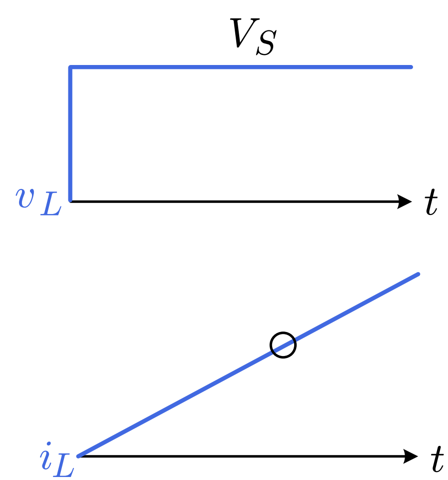
Voltage Drive of Inductor



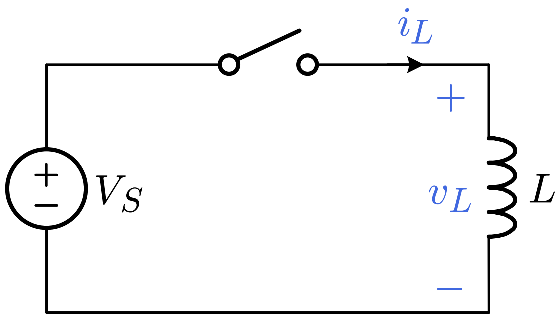
$$i_L(t) = \frac{1}{L}\int v_L(t)\,\mathrm{d}t$$

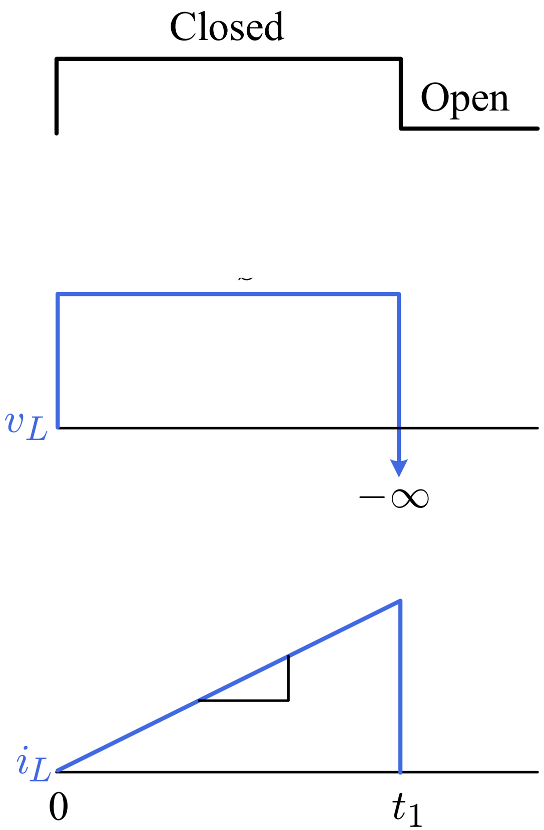
- Voltage drive: excitation of inductor with a voltage source





Inductive Switching Circuit #1

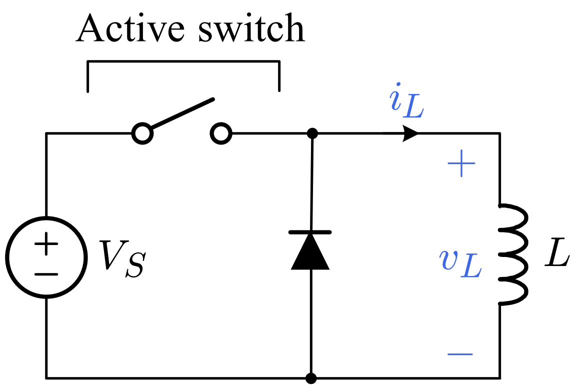


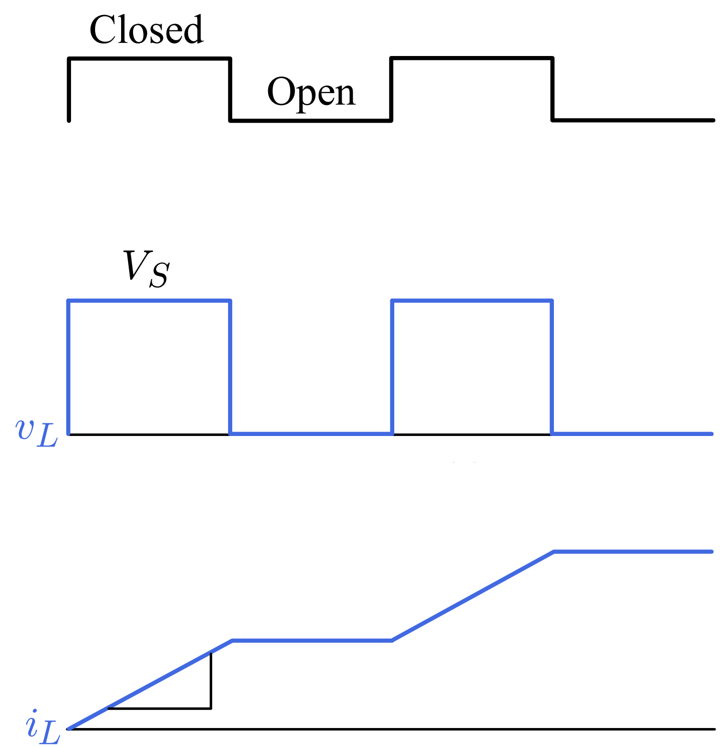


- Instantaneous release of the magnetic energy of

$\Rightarrow$

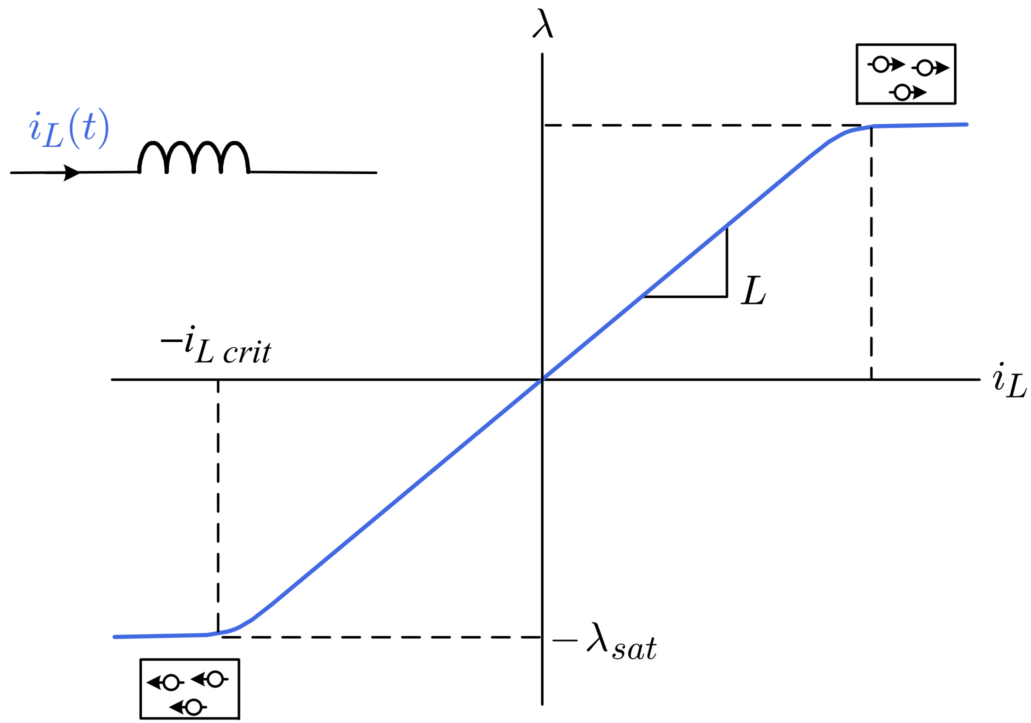
Inductive Switching Circuit #2





- When the active switch is opened, the diode is turned-on because the current-carrying inductor behaves as a current source.

Saturation of Inductor



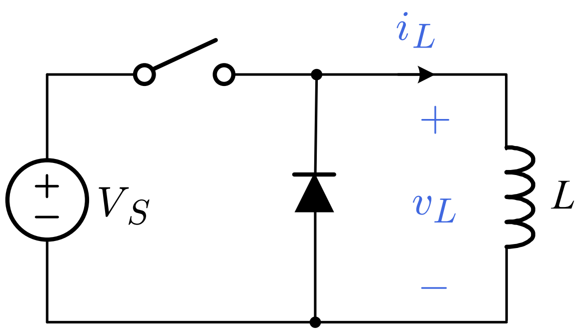
- Magnetic saturation

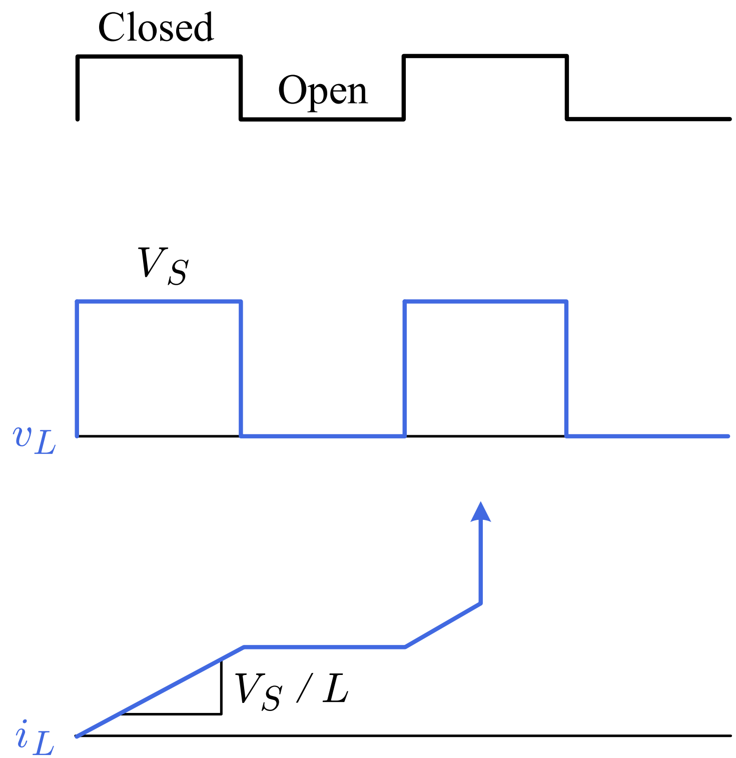
  When the current reaches the critical value, all the magnetic dipoles line up in parallel with the magnetic field and the magnetic flux saturates at its maximum value.

- Consequential effect of magnetic saturation

  Upon the magnetic saturation, the inductance becomes zero thereby causing a fatal failure of the circuit operation.

Saturation of Inductor

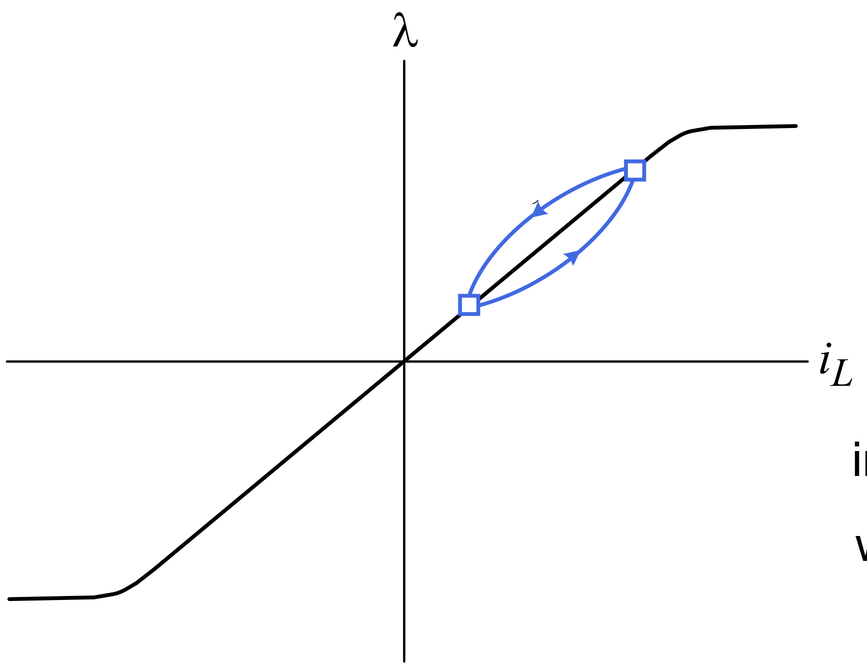




- When the current increase to $i_{L\,crit}$,

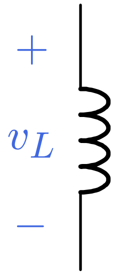
Flux Balance Condition

- Flux balance condition: the flux increase in one switching period should be equal to the flux decrease in that switching period.



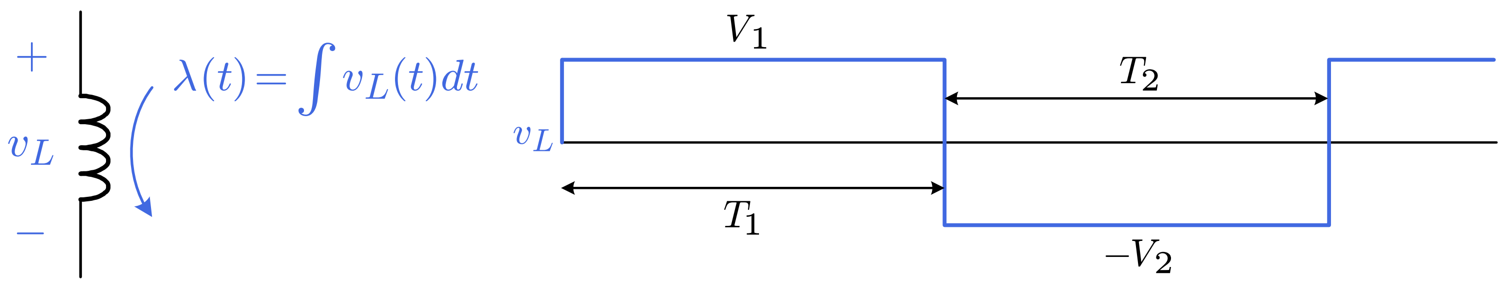
in order to avoid the flux walking towards saturation

- Faraday's law: $v_L(t) = \dfrac{\mathrm{d}\lambda}{\mathrm{d}t} \Rightarrow$



Volt-Sec Balance Condition

- Excitation of inductor with a rectangular voltage waveform



Volt-sec balance condition

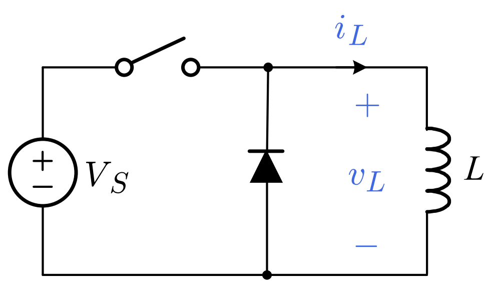
- The average value of the inductor voltage is considered to be zero assuming that the averaging is performed over a sufficiently longer period than the switching period.

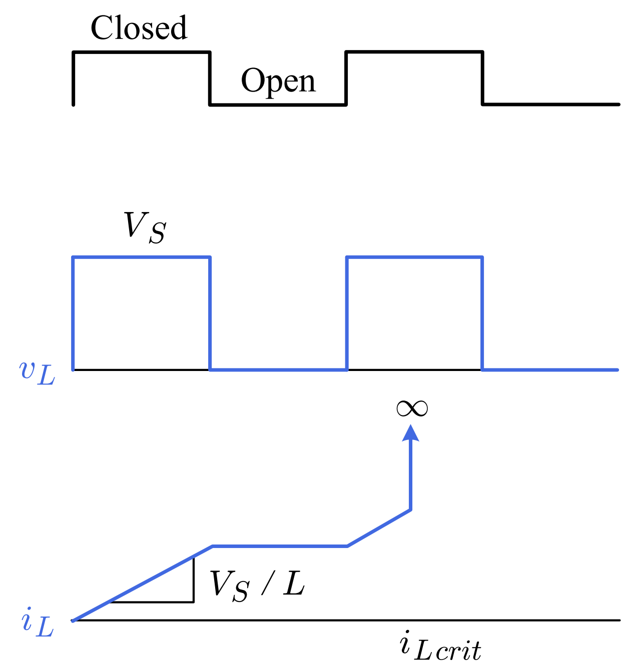
Implications of Volt-Sec Balance Condition

- Whenever possible, a switching circuit establishes a steady-state equilibrium by adjusting the circuit variables to satisfy the volt-sec balance condition on the inductors in the circuit.

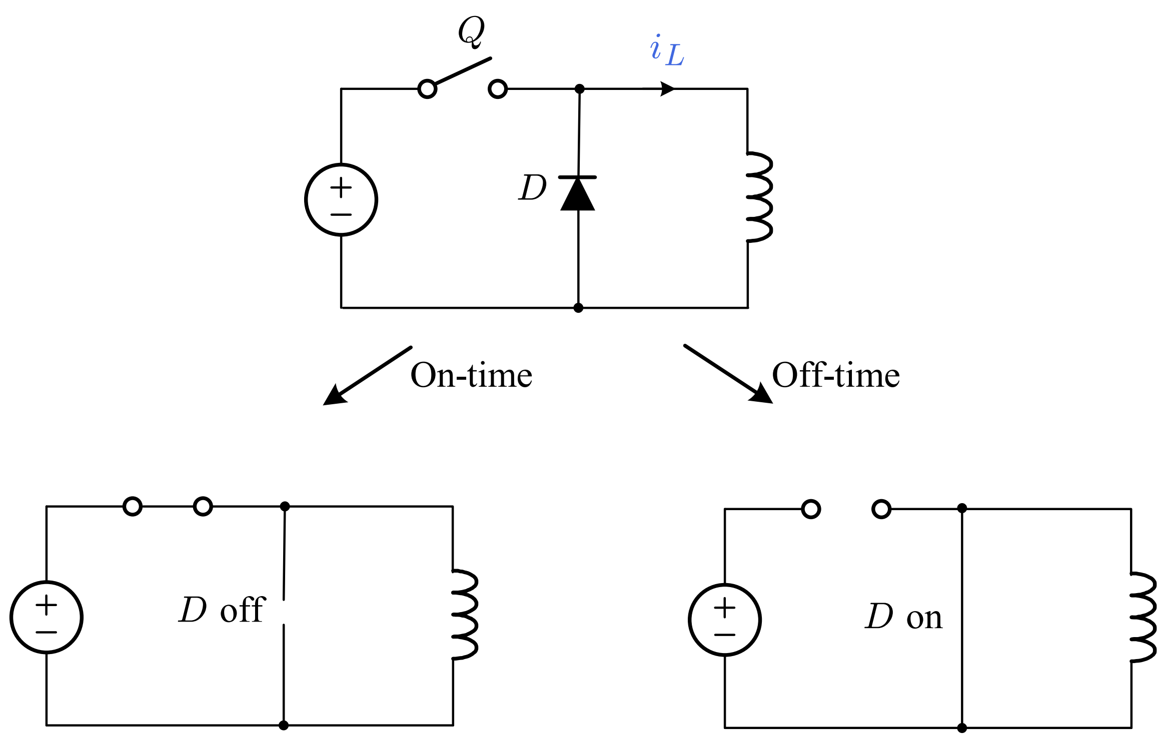
- A circuit that violates the volt-sec balance condition can be easily devised, but the circuit eventually destroys itself by an over-current condition that triggers the inductor saturation.

Example



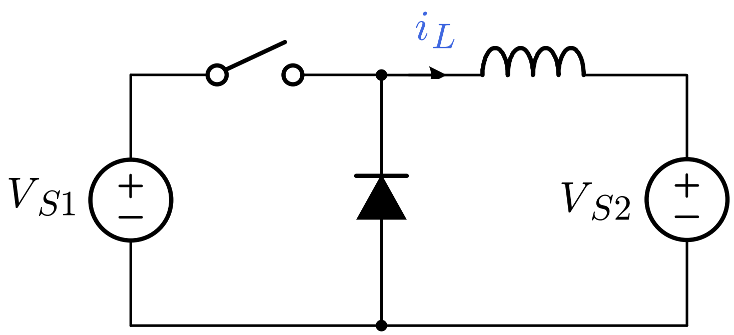


Freewheeling Path for Inductor Current

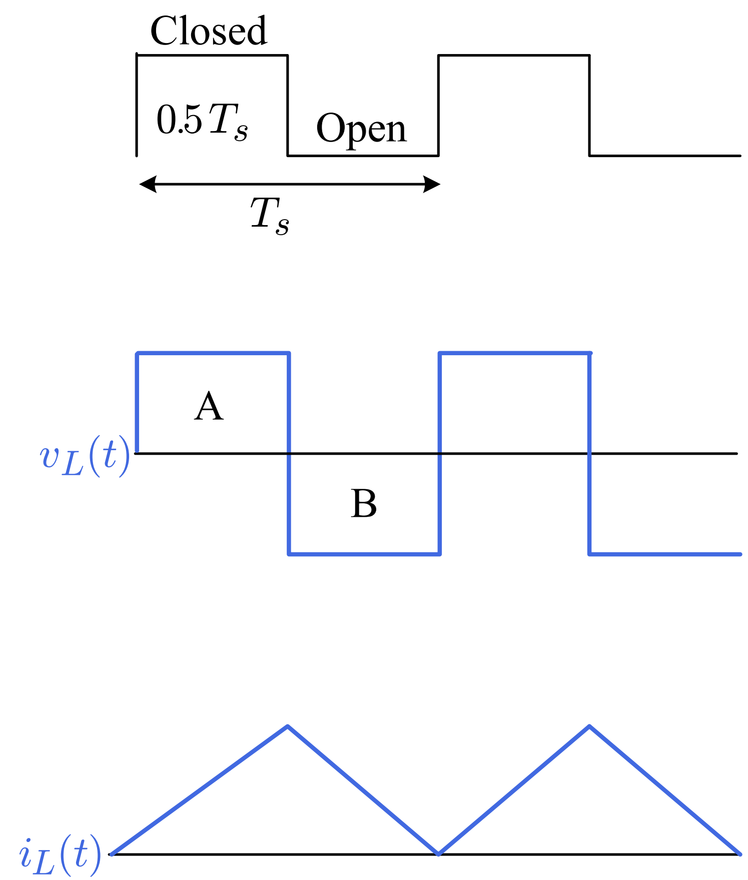


- When the on-time inductor current path is discontinued, the freewheeling path provides an alternative path for the inductor current.
- The freewheeling path is usually constructed with a diode, called the freewheeling diode.

Inductive Switching Circuit #3

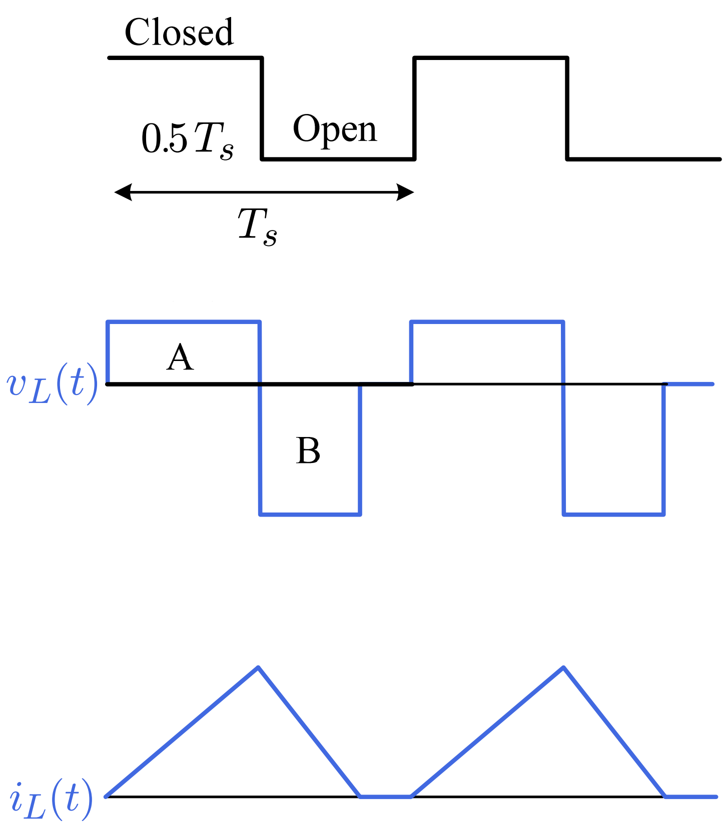


- Case #1 :

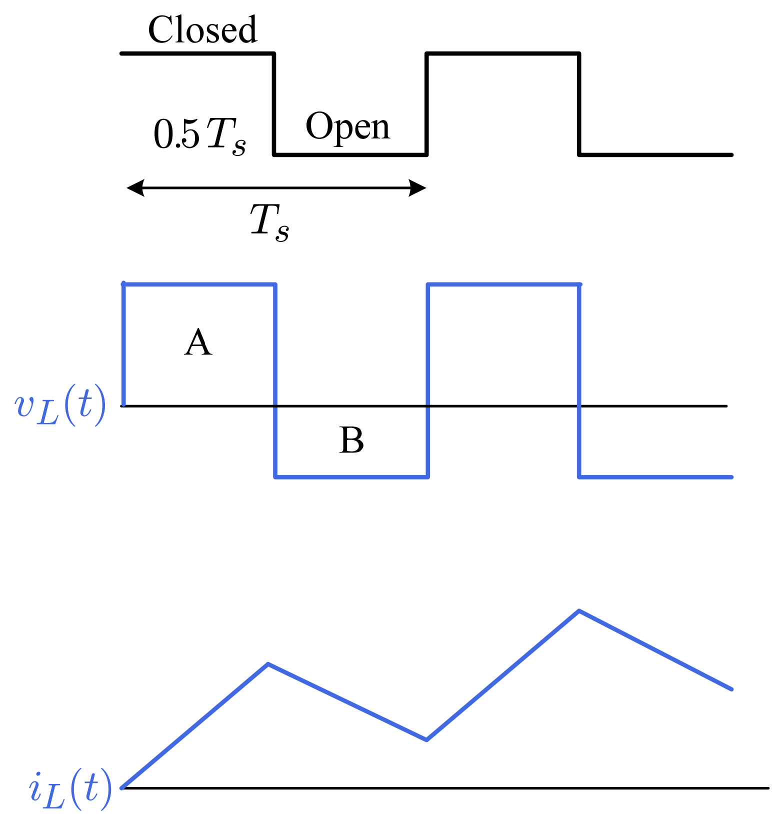


Inductive Switching Circuit #3

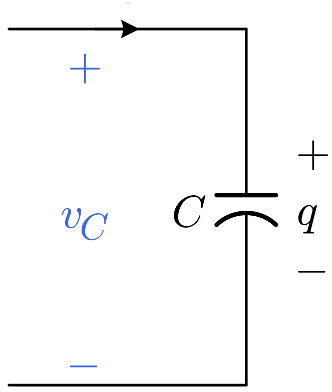
- Case #2 :



- Case #3 :



Definition of Capacitance

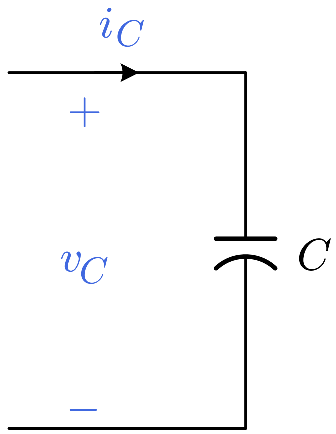


- Definition of capacitance:

- Definition of current:

- Circuit equation of capacitance

Circuit Equations for Capacitors



- Basic equations

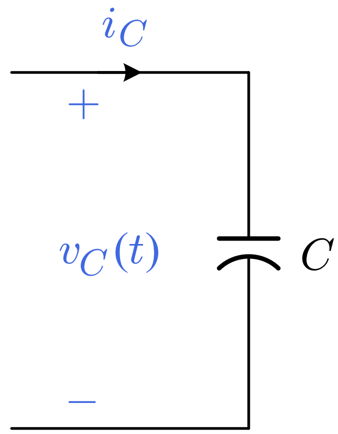
$$i_C(t) = C\,\frac{\mathrm{d}v_C(t)}{\mathrm{d}t}$$

- Special cases

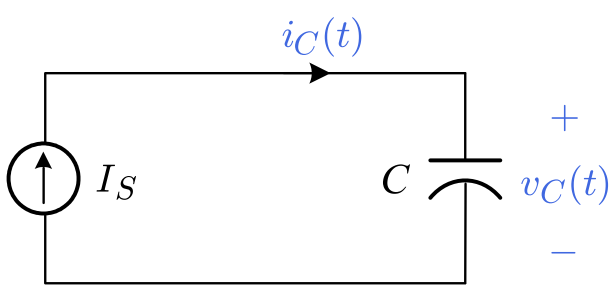
With $i_C(t) = I_S$,

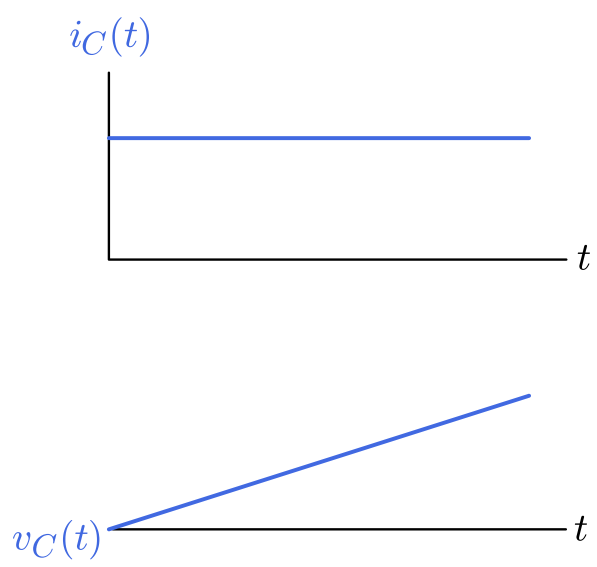
With $v_C(t) = V_S$,

Current Drive of Capacitor

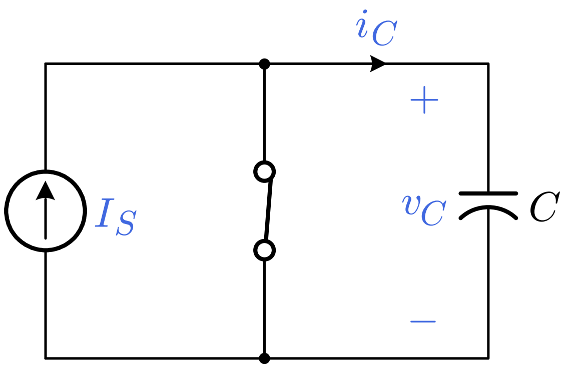


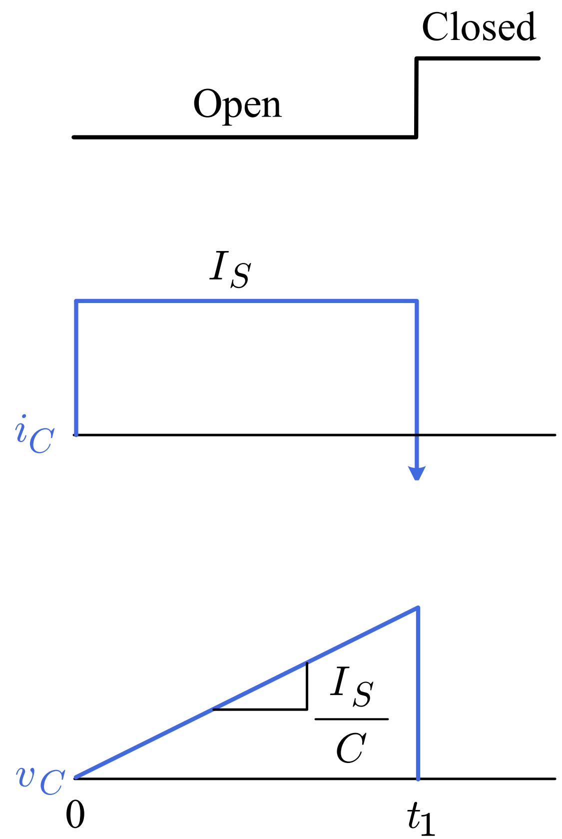
- Current drive: excitation of capacitor with a current source





Capacitive Switching Circuit #1

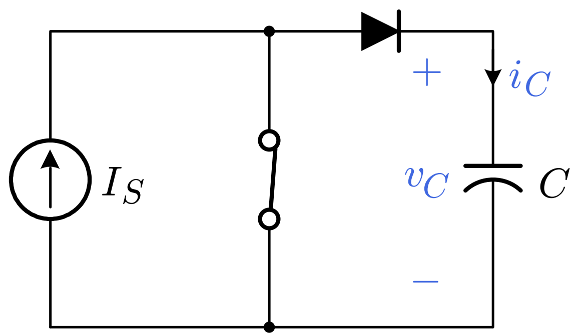


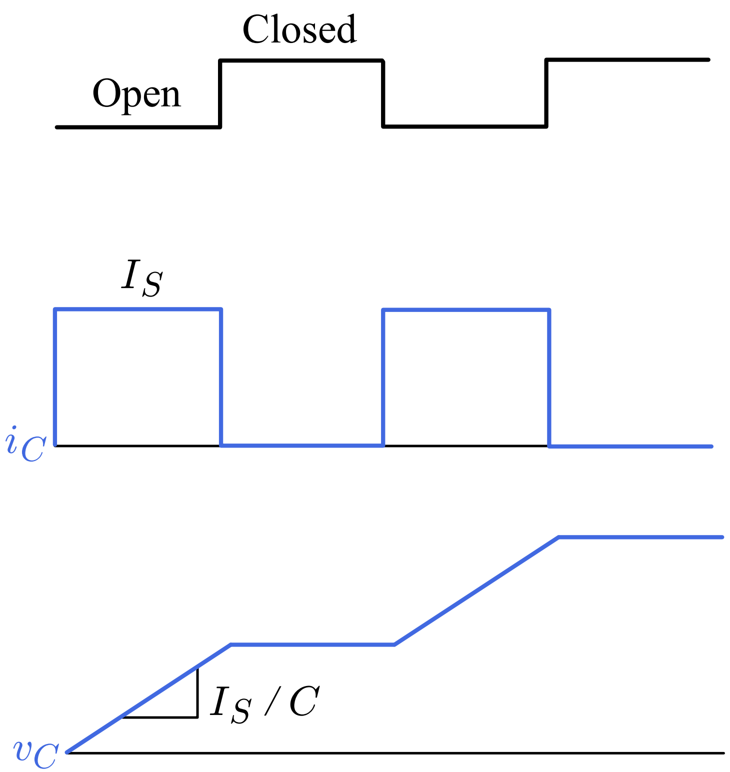


- Instantaneous release of the electric energy of

$\Rightarrow$ generation of a current spike that kills the switch

Capacitive Switching Circuit #2



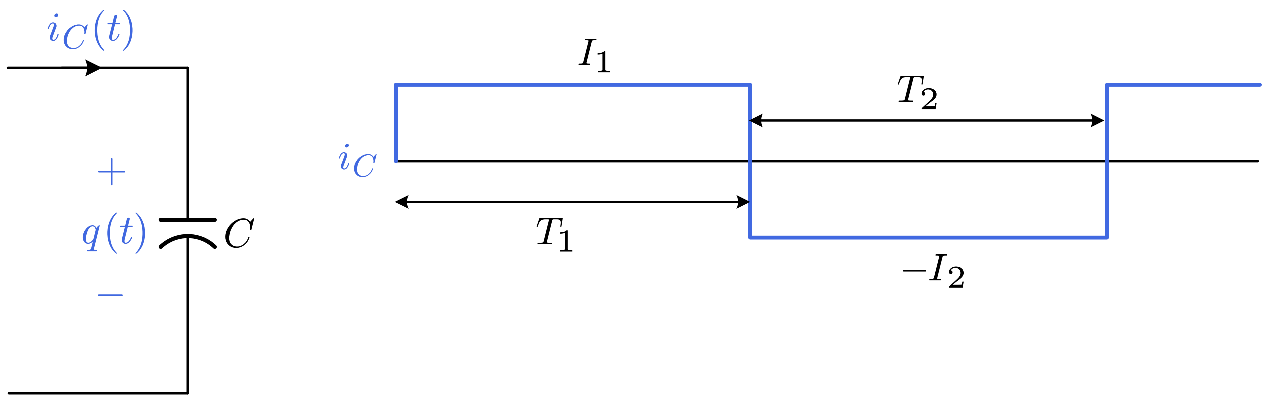


- Isolation diode blocks the capacitor voltage when the switch is closed.

Charge Balance Condition

- Charge balance condition: the charge increase in one switching period should be equal to the charge decrease in that switching period.

- Excitation of capacitor with a rectangular current waveform



Amp-sec balance condition

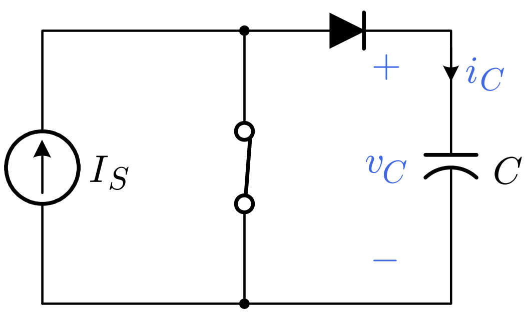
- The average value of the capacitor current can be considered to be zero assuming that the averaging is performed over a sufficiently longer period than the switching period.

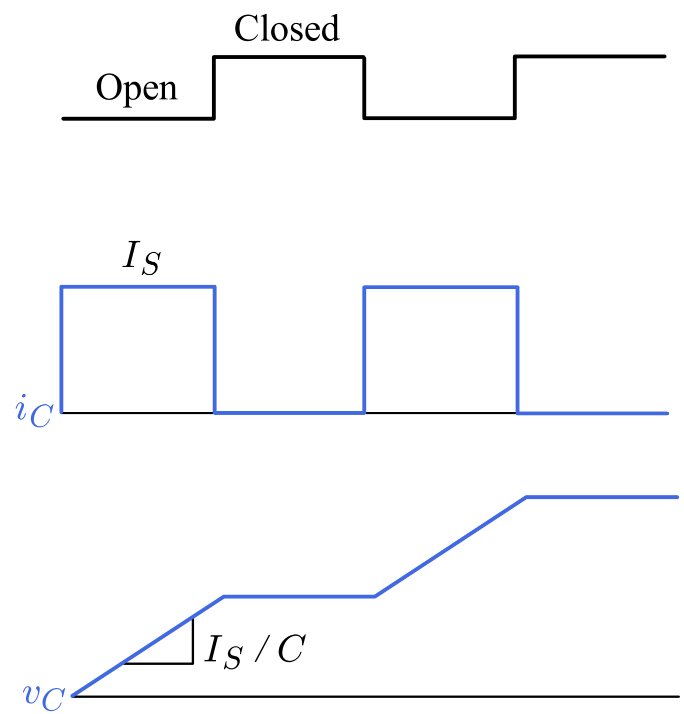
Implications of Amp-Sec Balance Condition

- Whenever possible, a switching circuit establishes a steady-state equilibrium by adjusting the circuit variables to satisfy the amp-sec balance condition on the capacitors in the circuit.

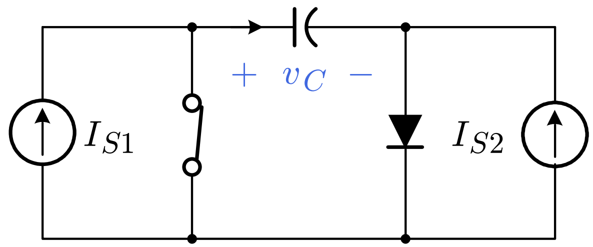
- A circuit that violates the amp-sec balance condition can be easily devised, but the circuit eventually destroys itself by an over-voltage condition on the capacitor.

Example



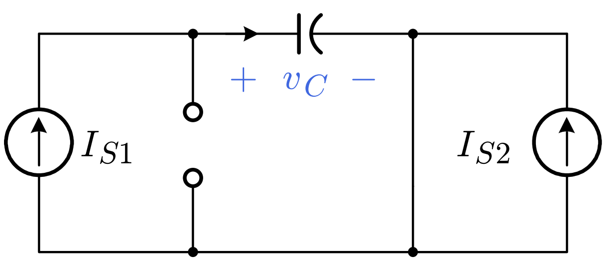


Capacitive Switching Circuit #3

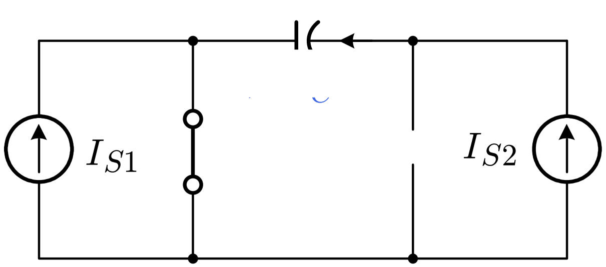


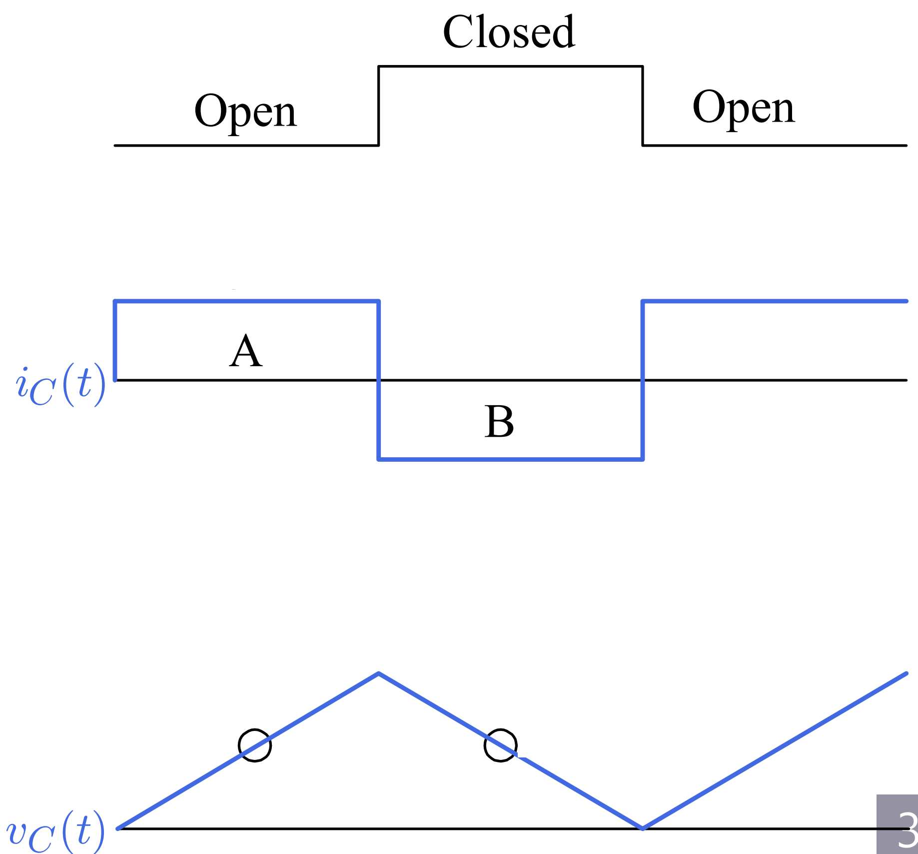
- Case #1:

Switch open



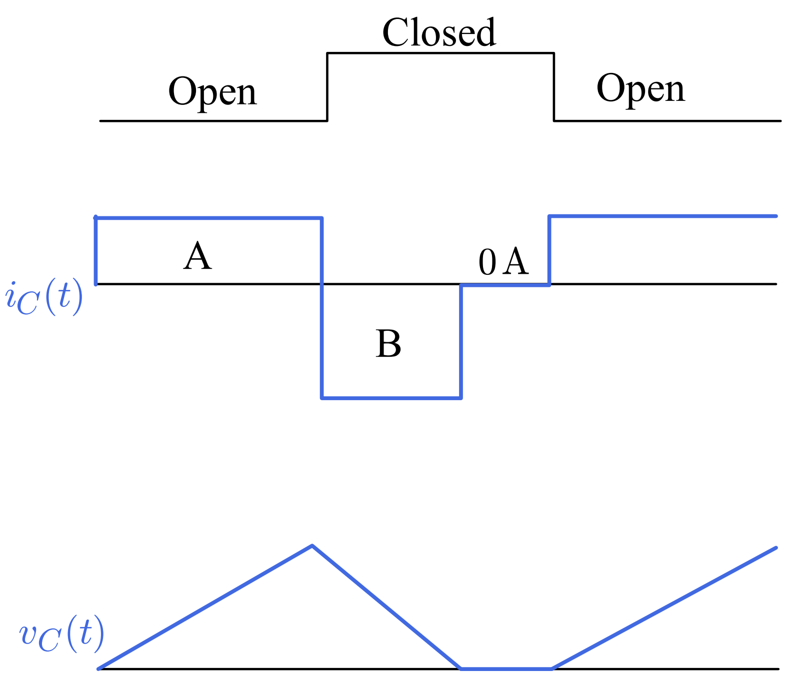
Switch closed



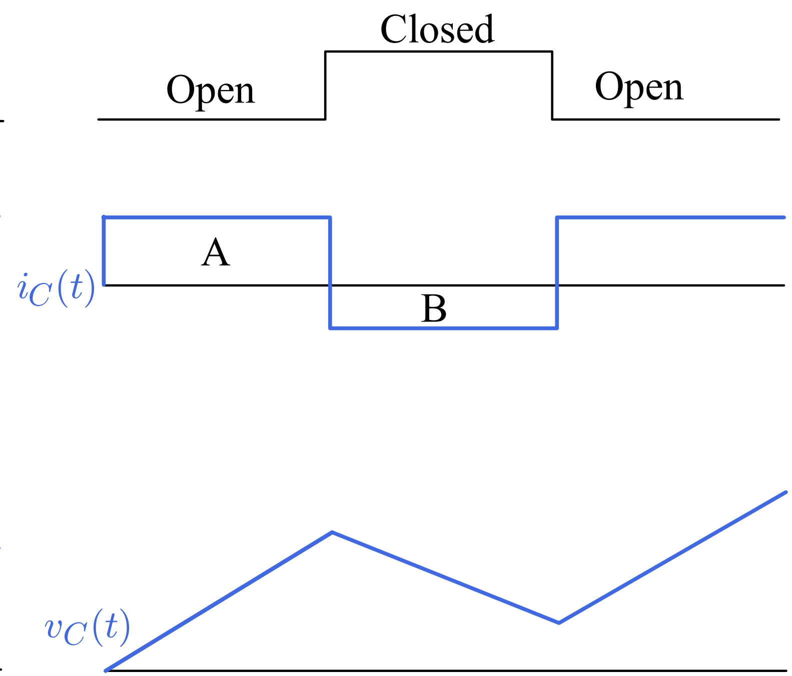


Capacitive Switching Circuit #3

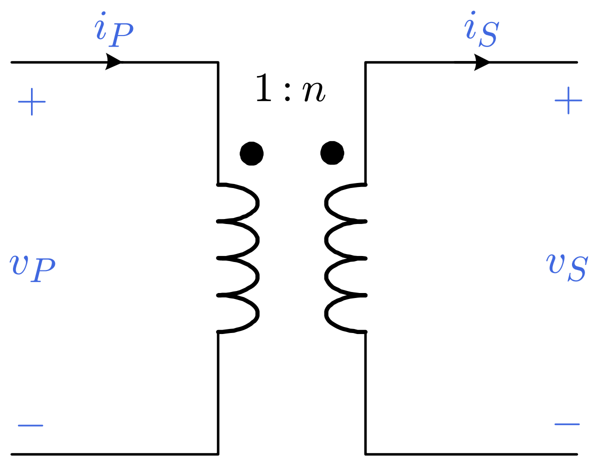
- Case #2 :



- Case #3 :



Ideal Transformer



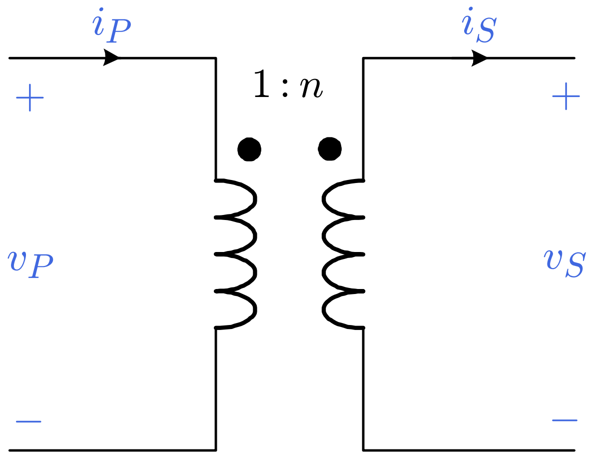
- Definition of circuit variables

  $v_P(t)$: primary voltage $i_P(t)$: primary current

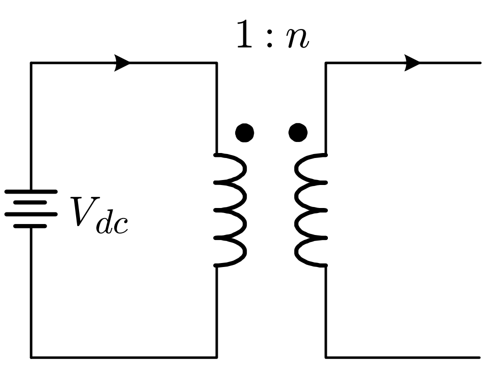
  $v_S(t)$: secondary voltage $i_S(t)$: secondary current

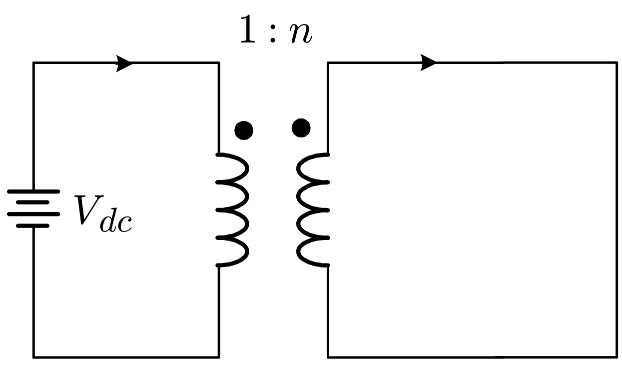
- Definition of circuit equation

Circuit Equations of Ideal Transformer

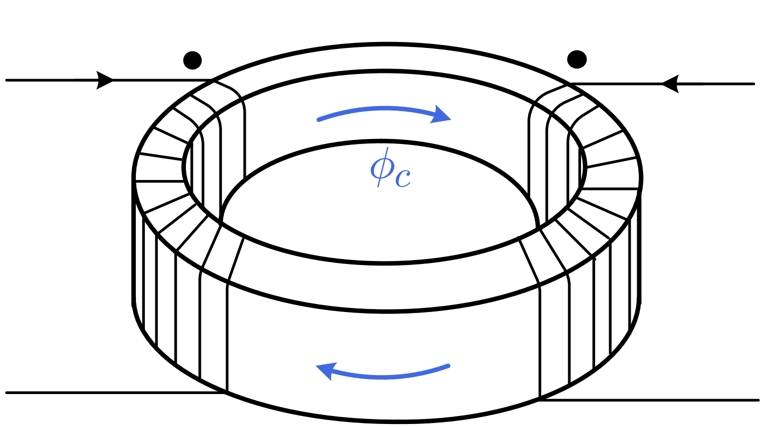


- Examples

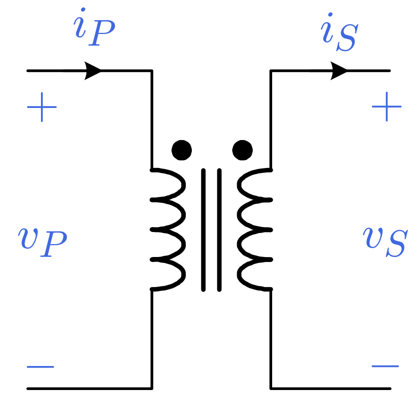




Practical Transformer



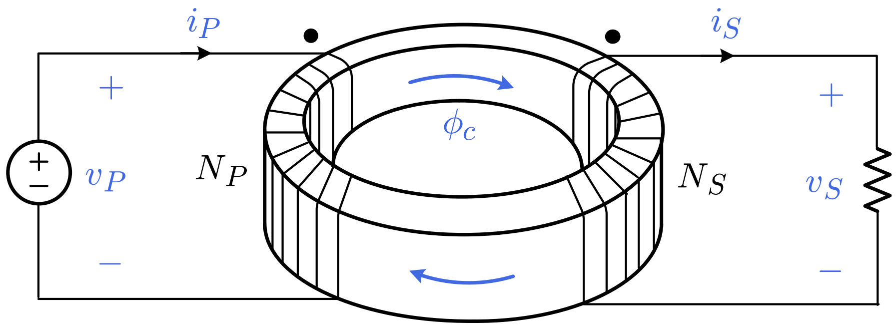
Structure and dot convention

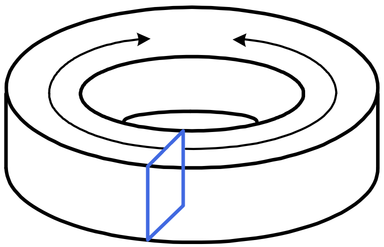


Symbol and polarity

- Dot convention: the primary and secondary currents flowing into the winding terminals marked ● produce a mutually additive magnetic flux.
- Lenz`s law: an electro-magnetic induction occurs in such a way that the magnetic flux produced as the outcome of the magnetic induction opposes the magnetic flux that initiated the induction process.

Modeling of Practical Transformer

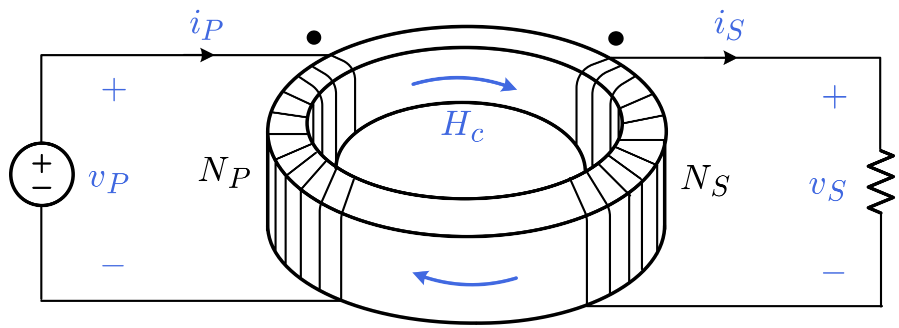


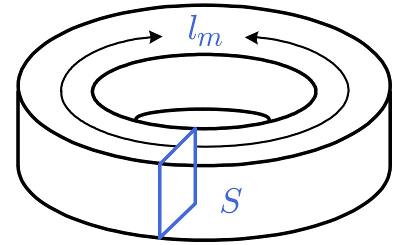


ϕ_c : magnetic flux inside the core

1) Faraday`s law

Modeling of Practical Transformer





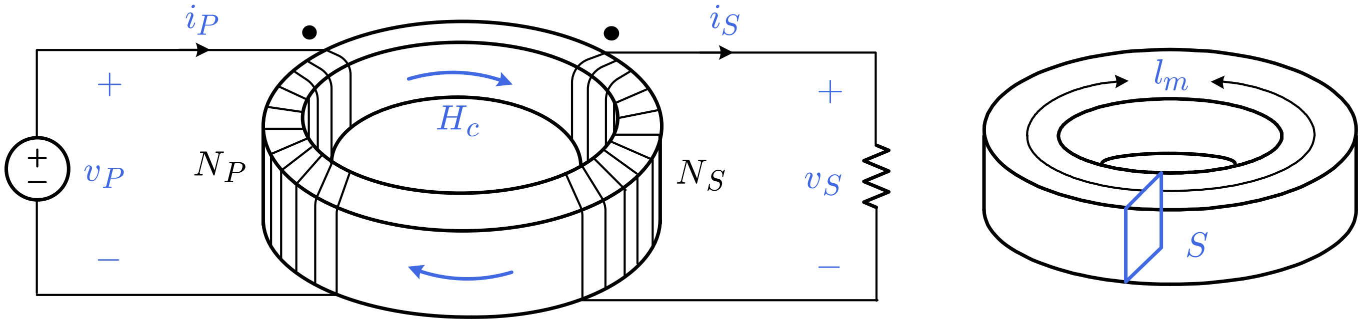
H_c : magnetic field intensity inside the core

l_m : mean magnetic path length

2) Ampere`s law

Magnetizing current $i_m(t)$: the current required to create $H_c(t)$ that couples the primary and secondary windings through magnetic induction.

Modeling of Practical Transformer



3) Magnetizing inductance

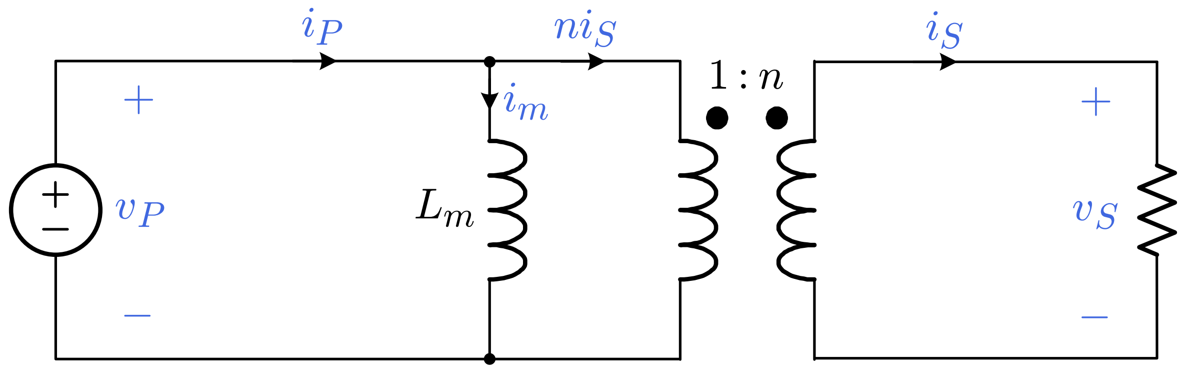
Magnetizing current through primary winding

Magnetic flux linkage at primary winding

Magnetizing inductance L_m associated with $i_m(t)$ and $\lambda_P(t)$

Circuit Model of Practical Transformer

4) Circuit model



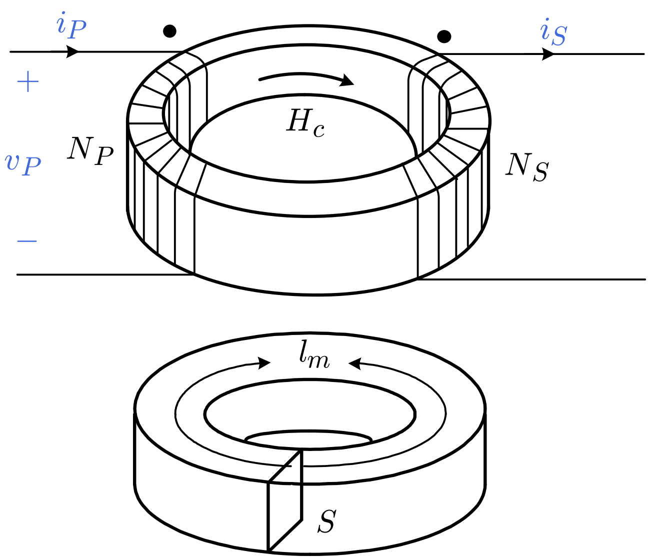
Voltage equation

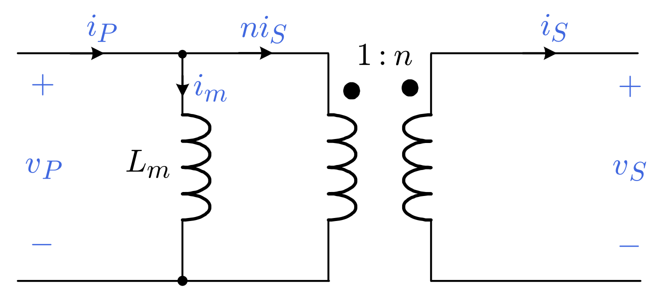
Turns ratio $n = \dfrac{N_S}{N_P}$

Current equation

Summary of Transformer Modeling

- Circuit model



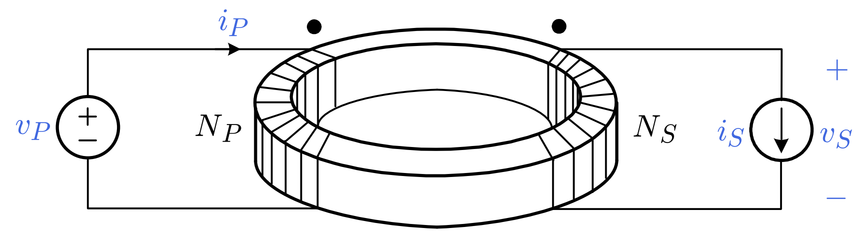


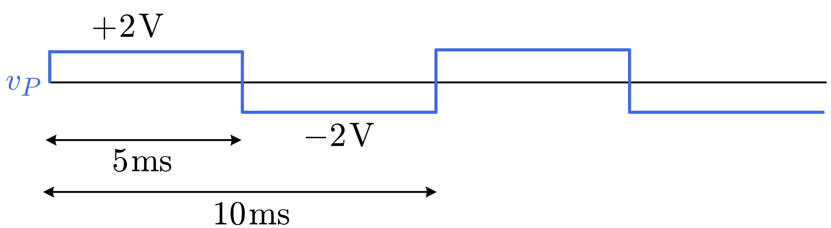
Voltage equation

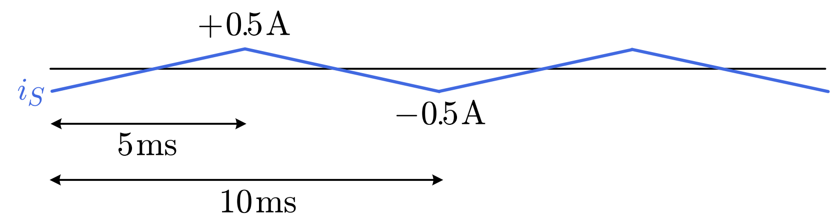
Current equation

When μ_r is assumed infinite, L_m becomes infinitely large and the circuit model reduces to the ideal transformer.

Example of Transformer Circuit





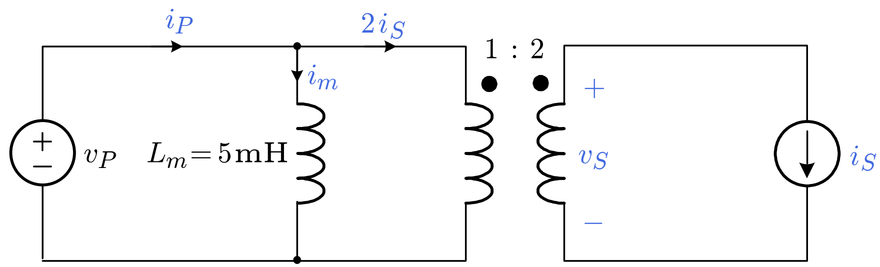


- Transformer parameters

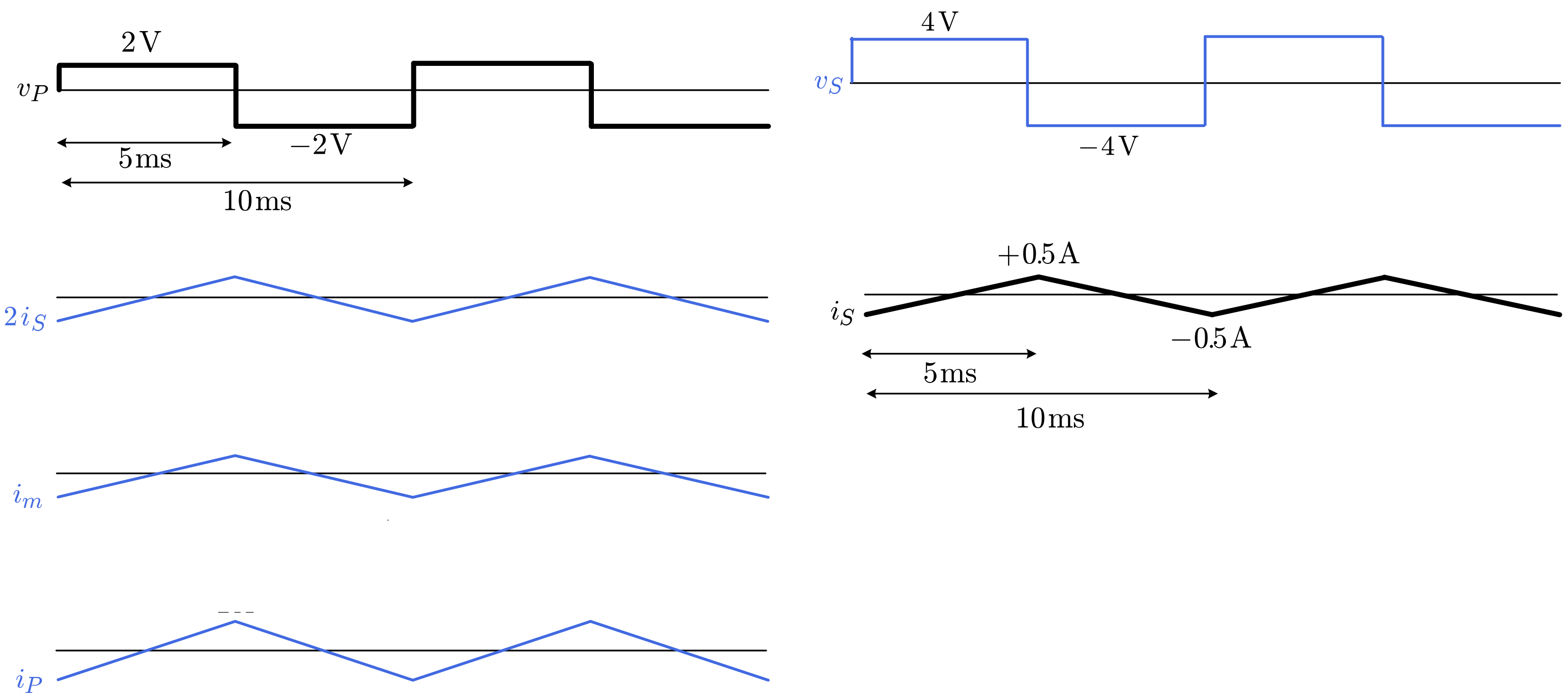
$\mu_r = 5\times10^3 \quad S = 1\ \mathrm{cm}^2 \quad l_m = 4\pi\times10^{-1}\,\mathrm{cm} \quad N_P = 10 \quad N_S = 20$

- Circuit parameters

Example of Transformer Circuit

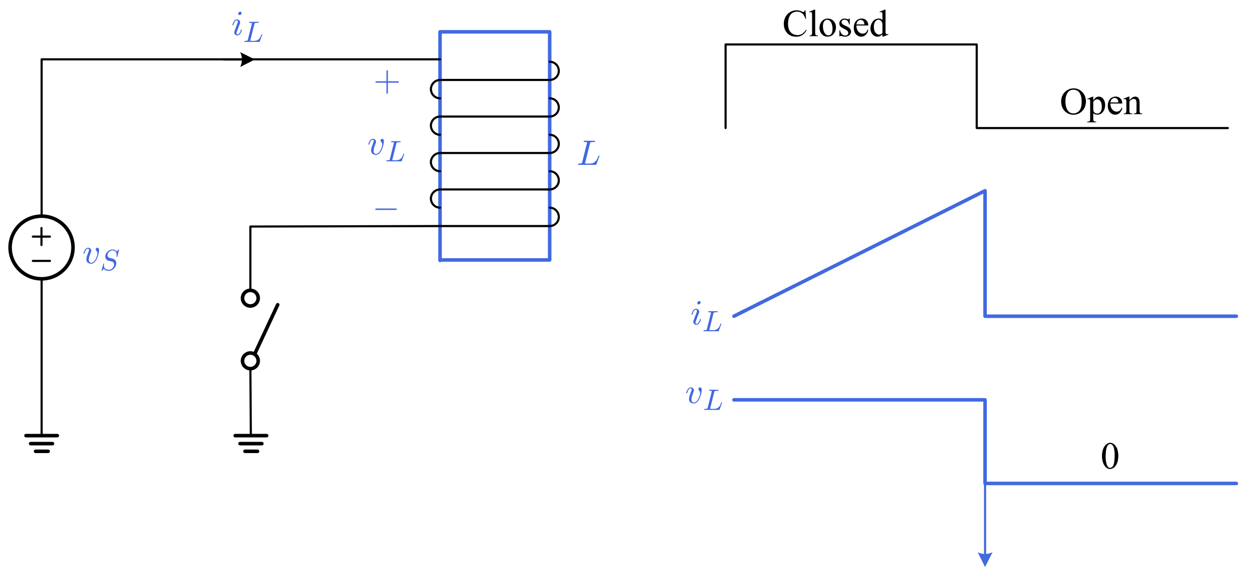


- Circuit waveforms



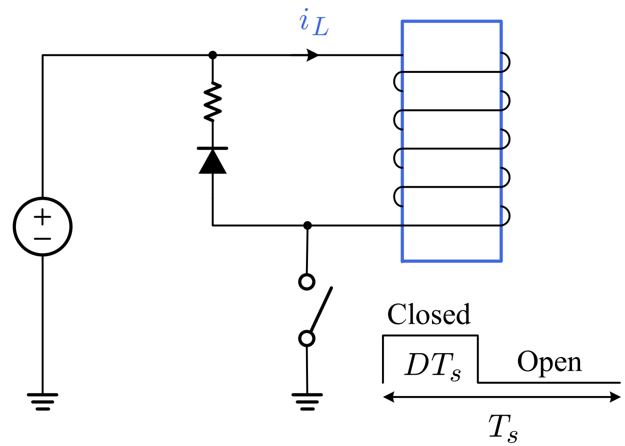
Solenoid Drive Circuit

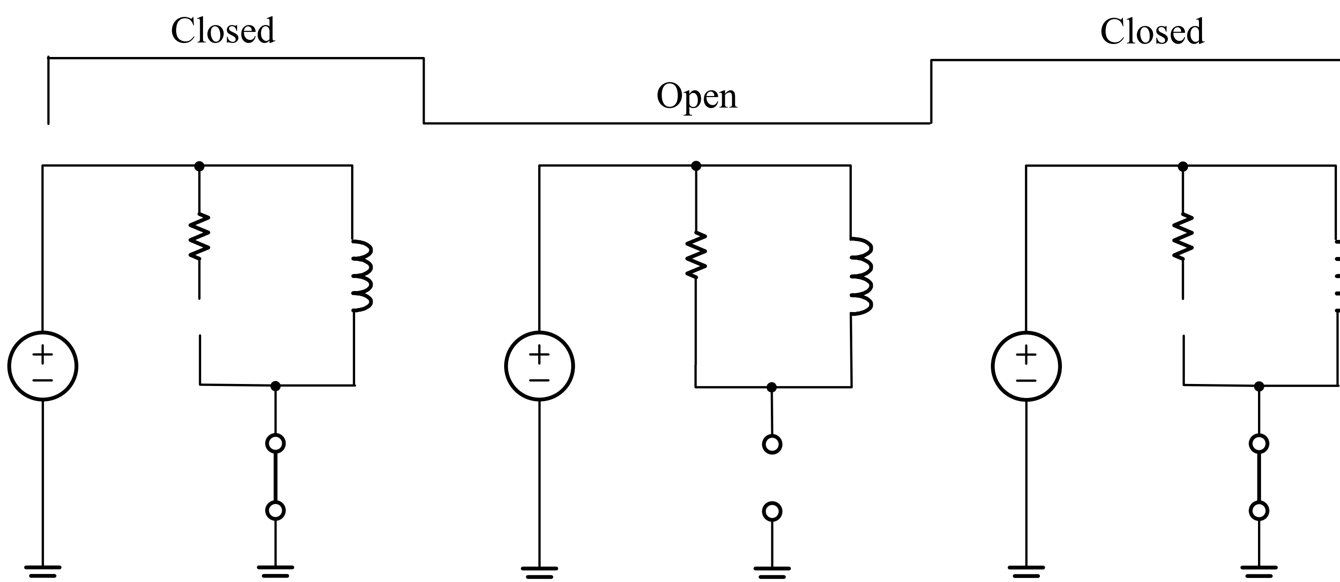
- Solenoid: an inductor fabricated by winding copper coil around an iron core
- Conceptual (faulty) solenoid drive circuit



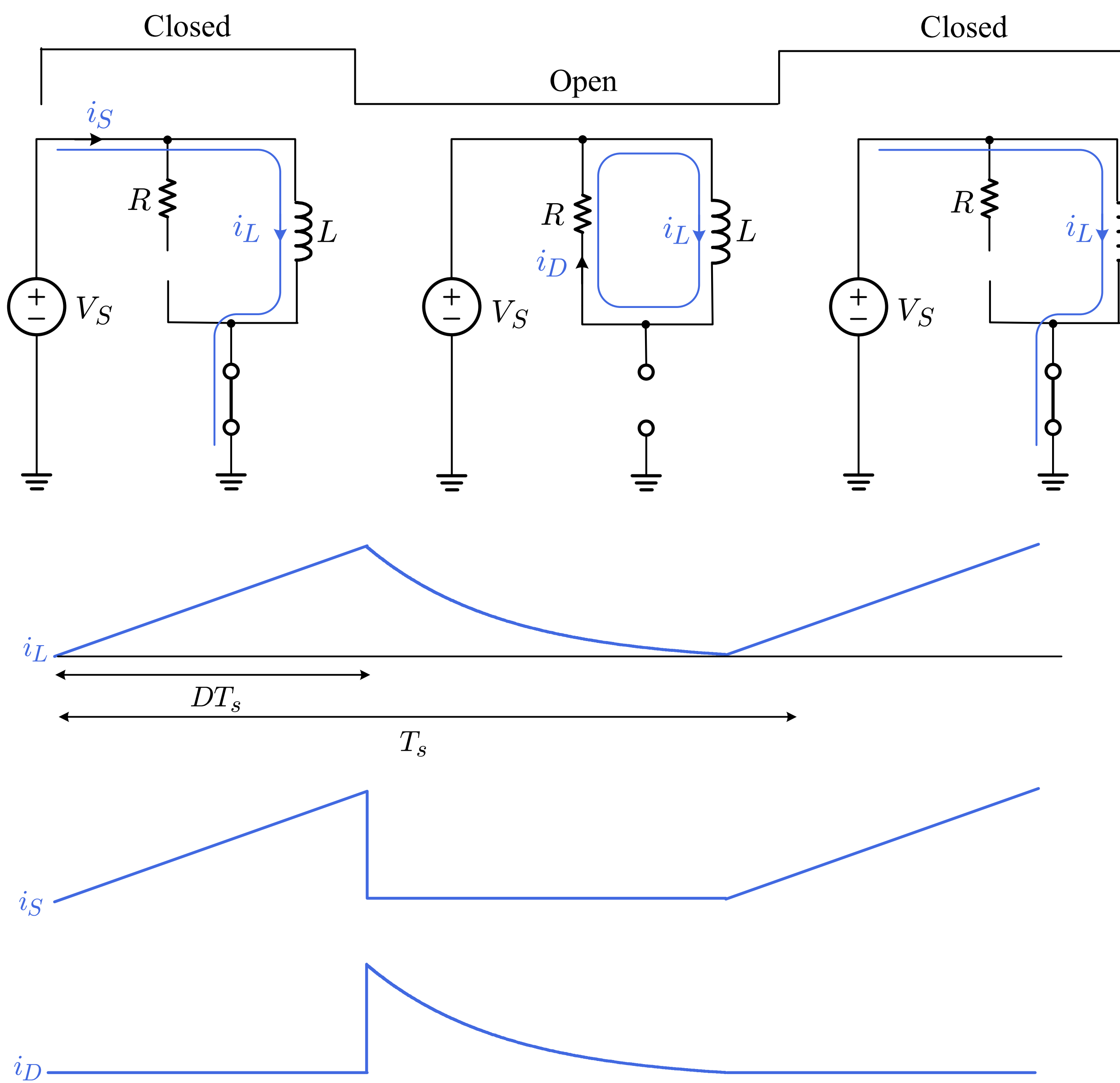
- Solenoid drive circuit must be designed so that the remnant energy is safely removed from the solenoid inductance.

Dissipative Solenoid Drive Circuit

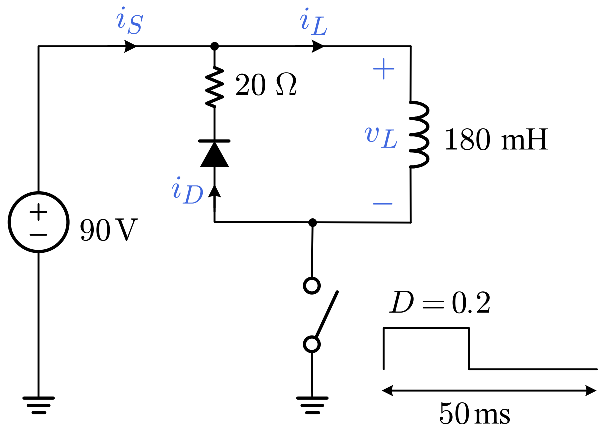


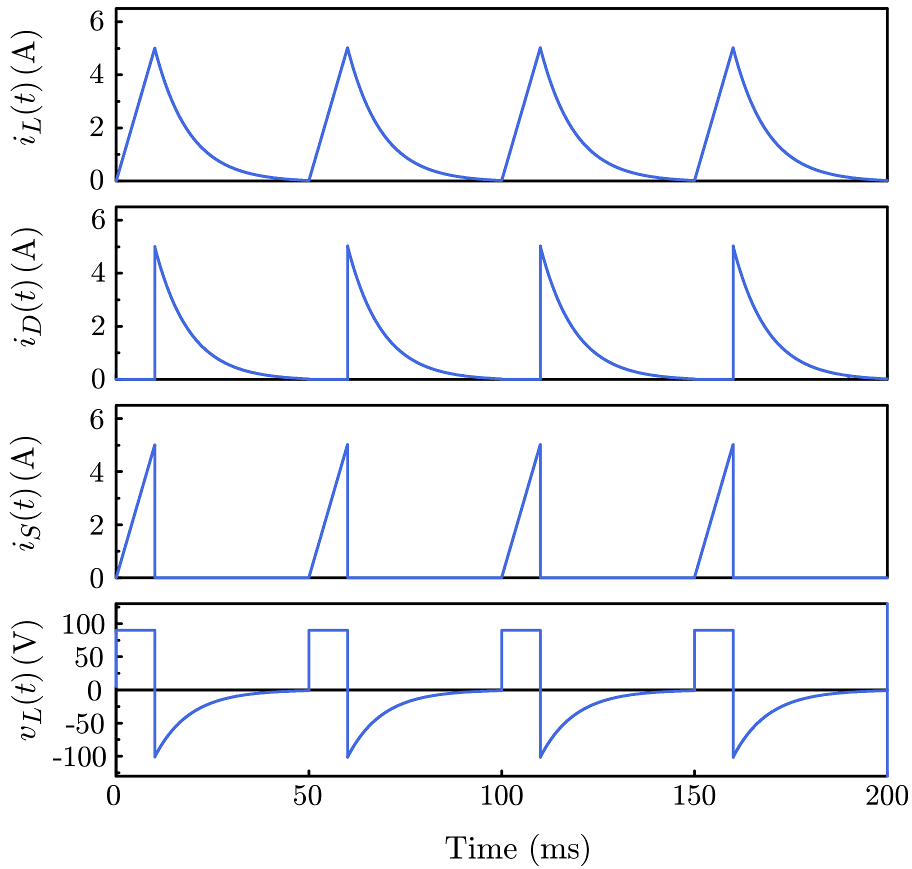


Dissipative Solenoid Drive Circuit



Example of Dissipative Solenoid Drive Circuit





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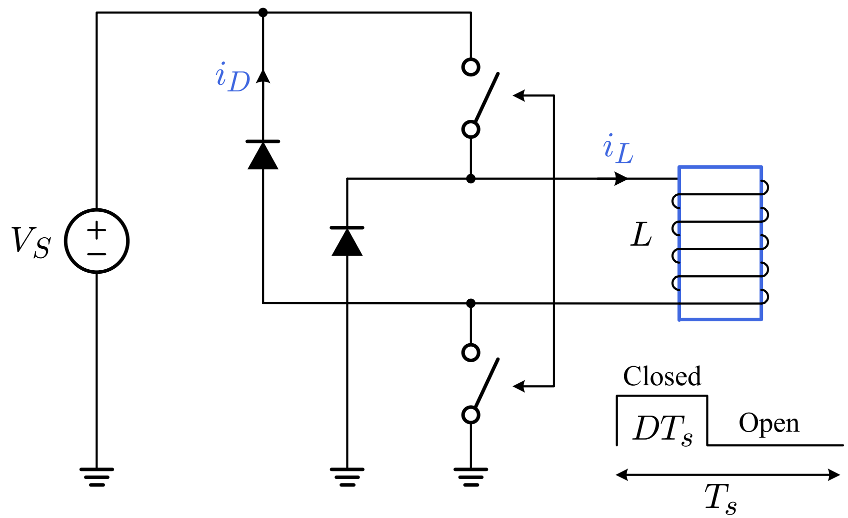
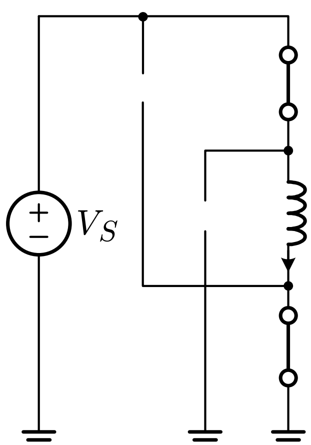
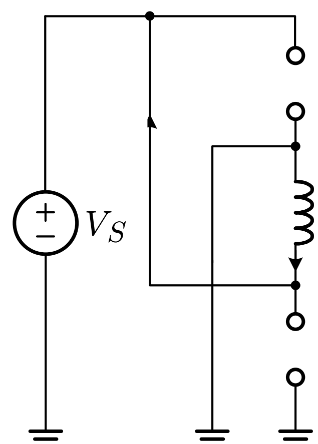
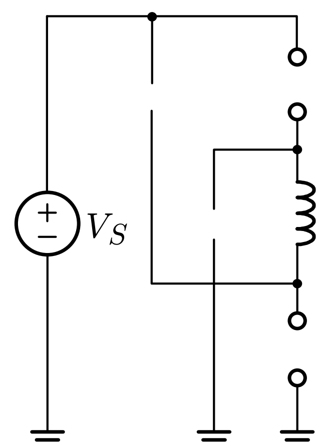
Non-Dissipative Solenoid Drive Circuit

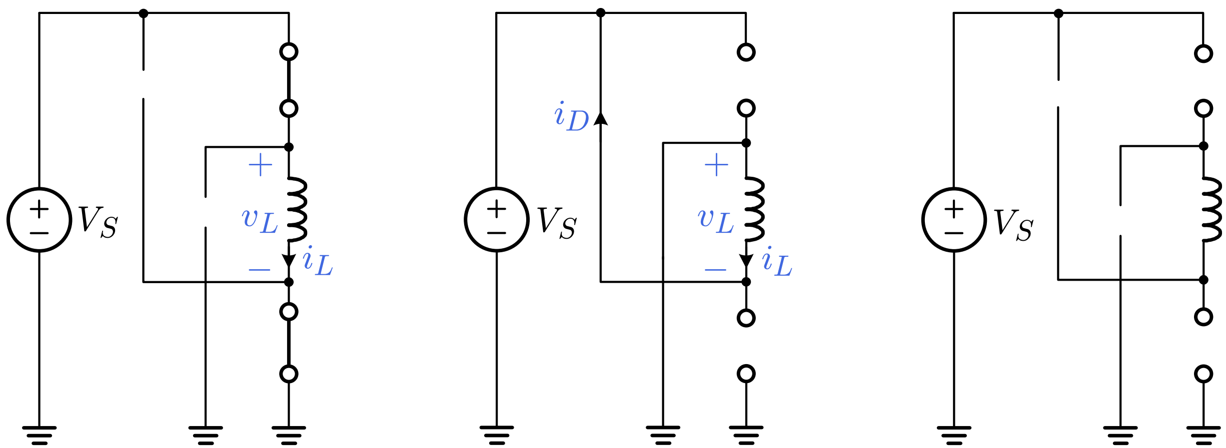


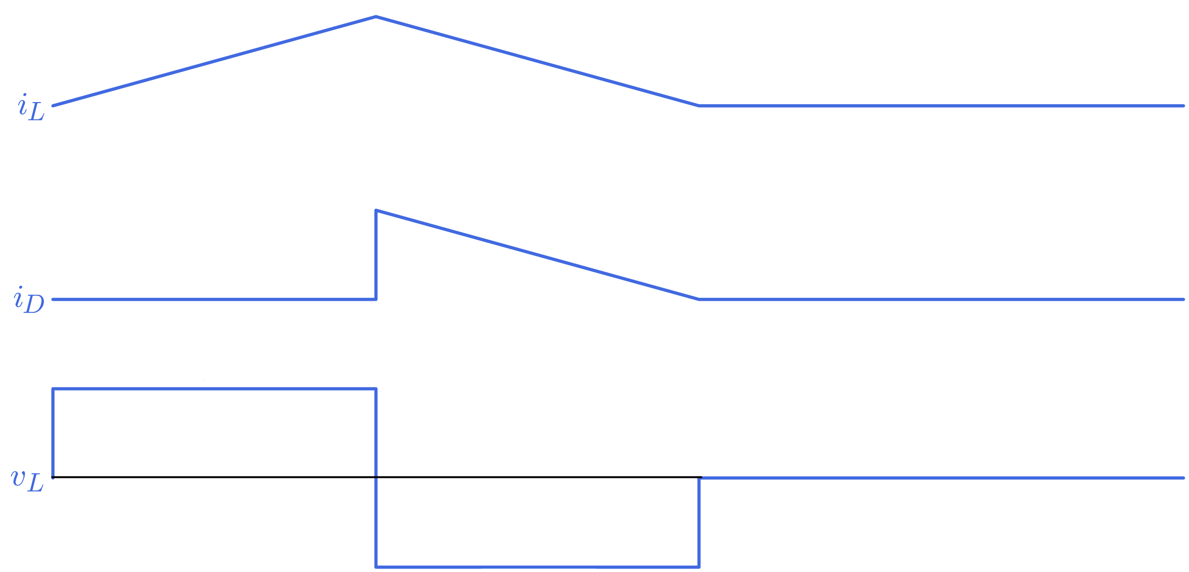




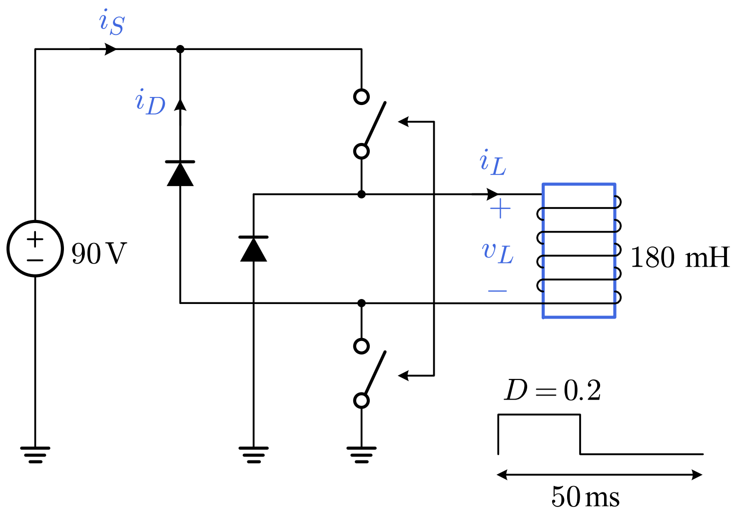


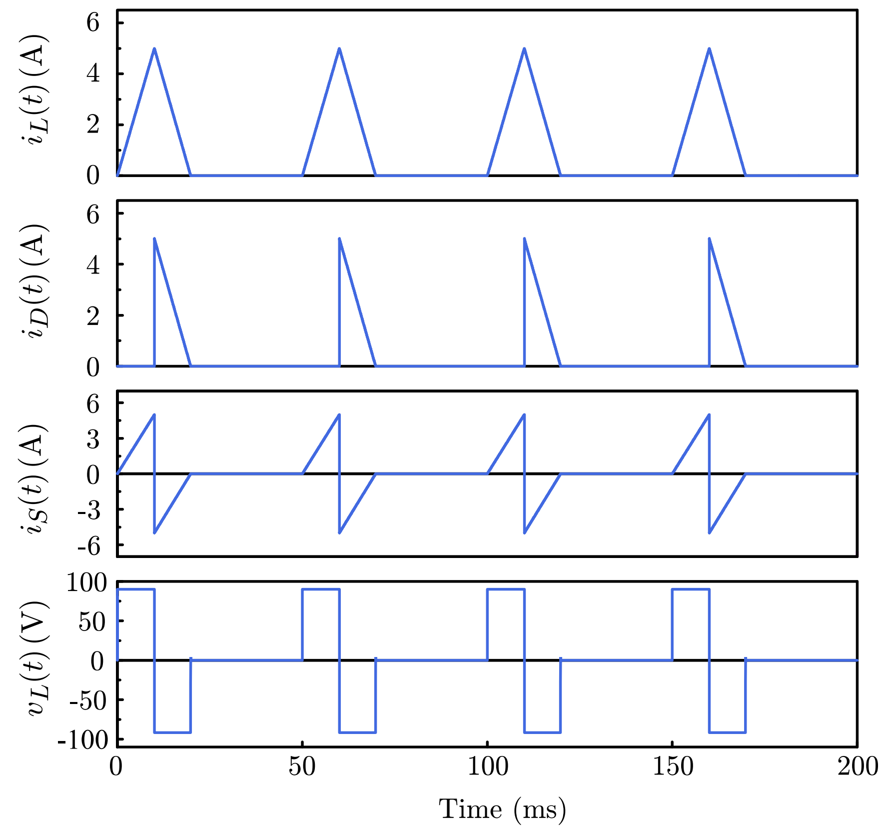
Non-Dissipative Solenoid Drive Circuit





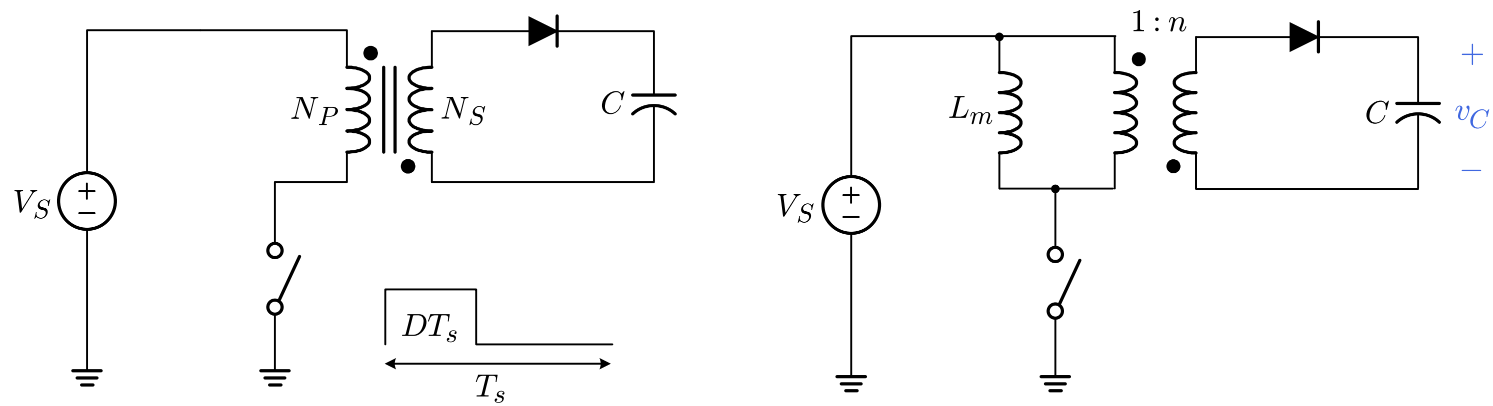
Example of Non-Dissipative Solenoid Drive Circuit



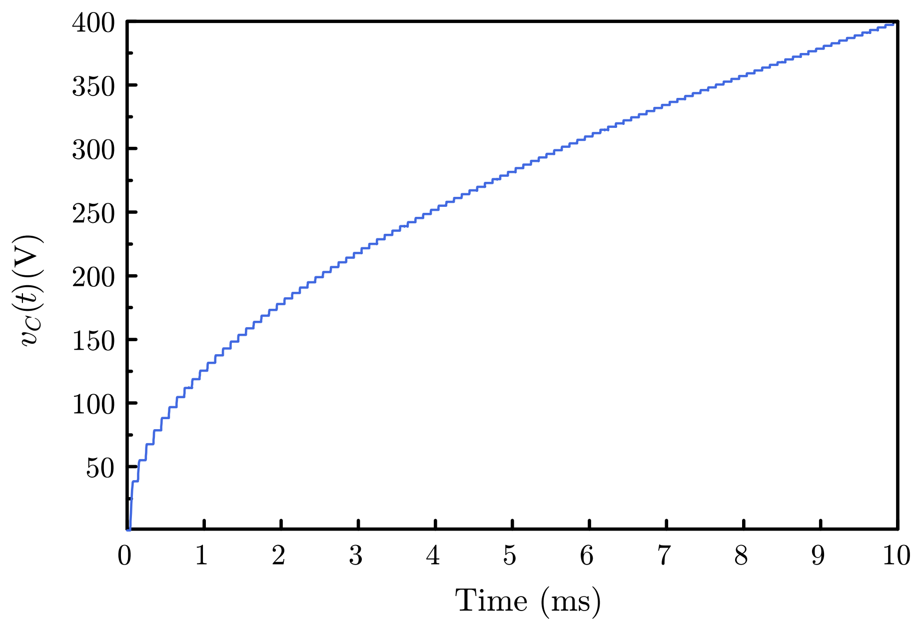


Capacitor Charging Circuit

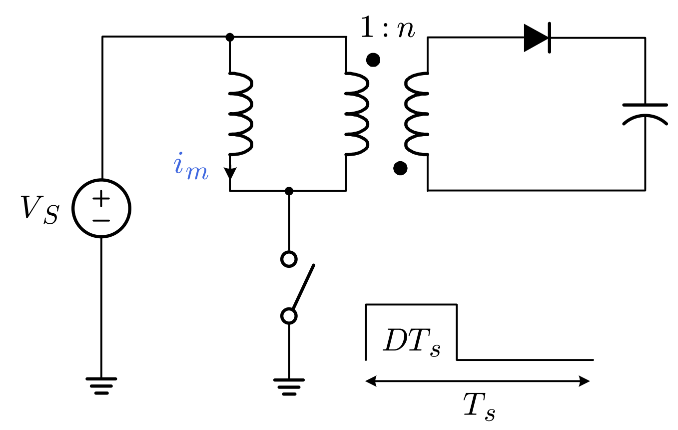
- Circuit configuration

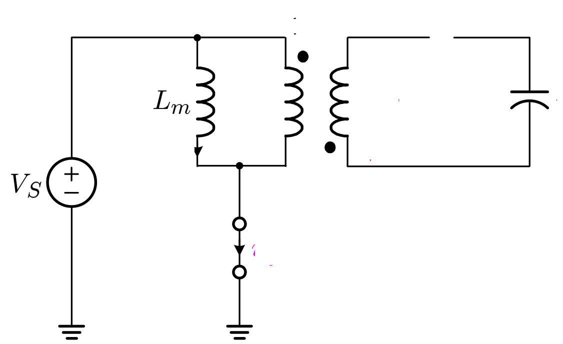


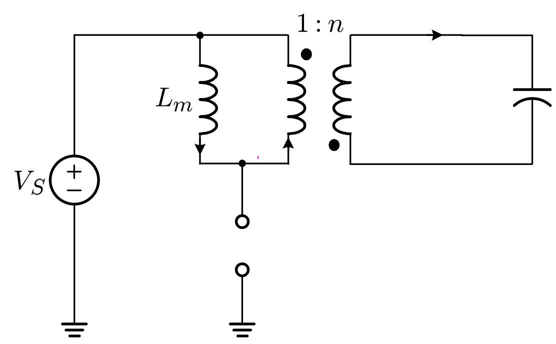
- Operation example

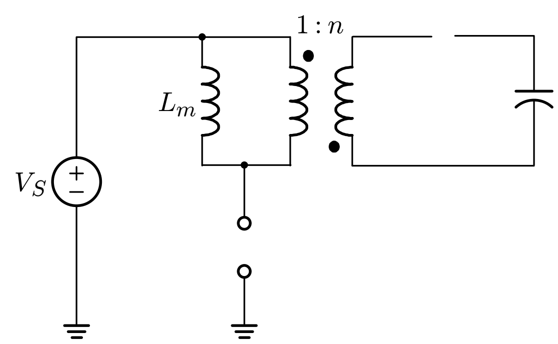


Capacitor Charging Circuit

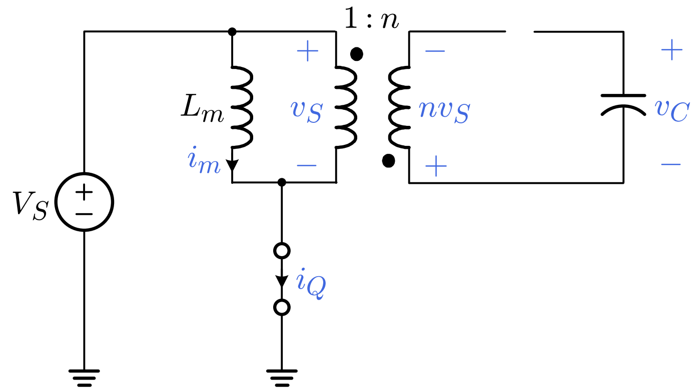




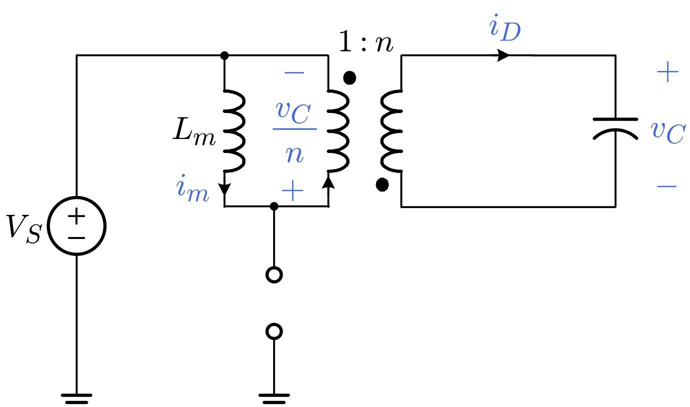




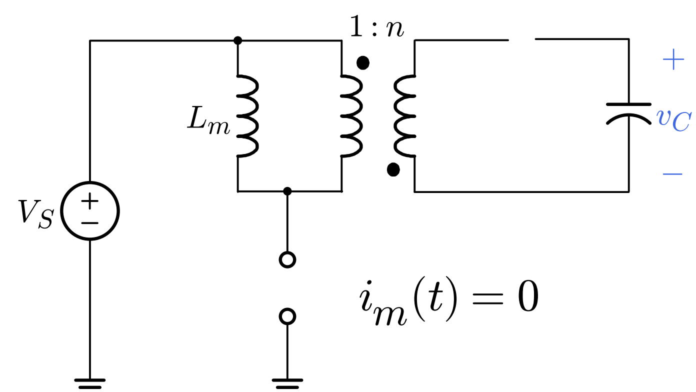
Capacitor Charging Circuit



Energy build-up

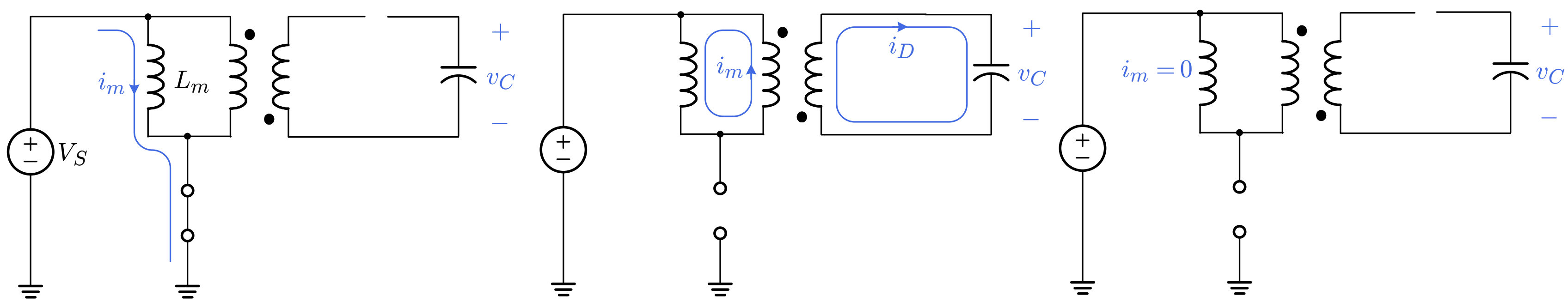


Energy transfer

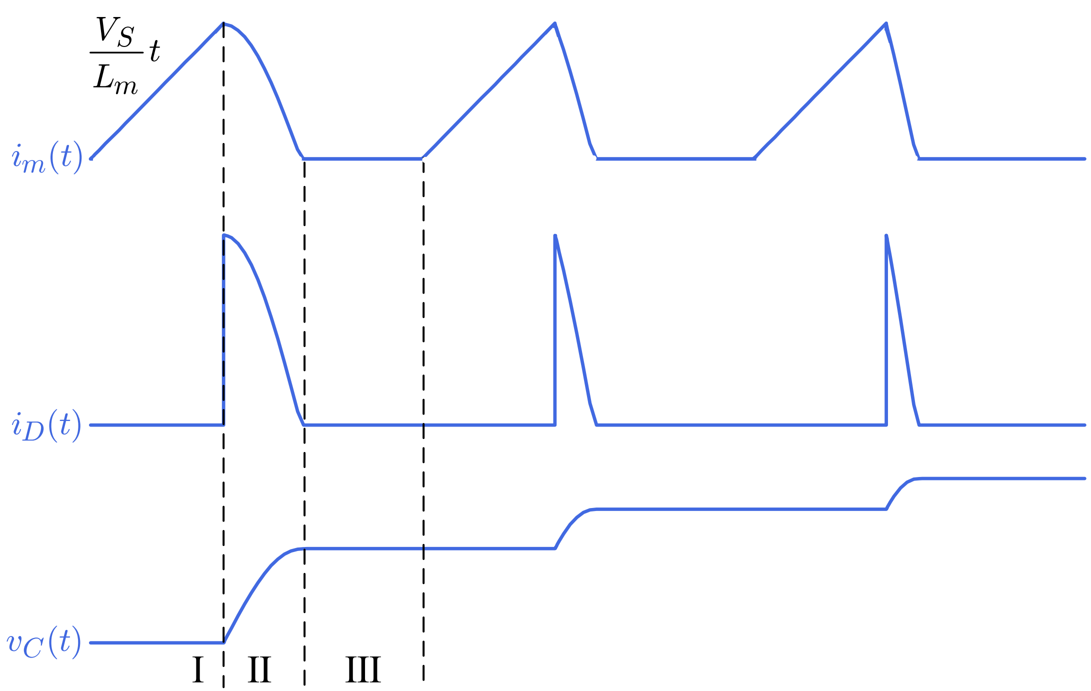


Recess period

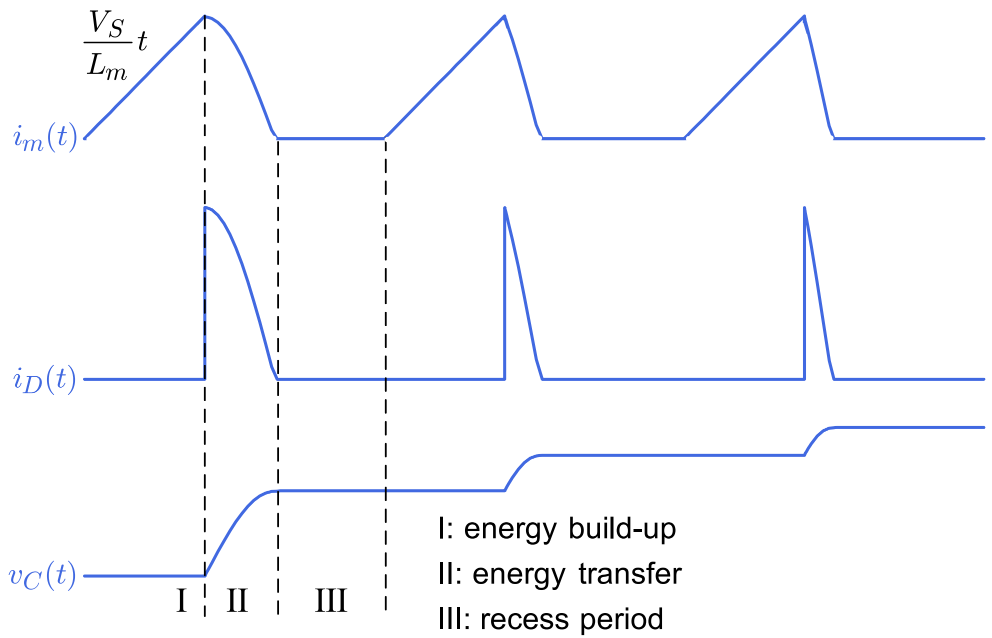
Capacitor Charging Circuit



Energy build-up   Energy transfer   Recess period

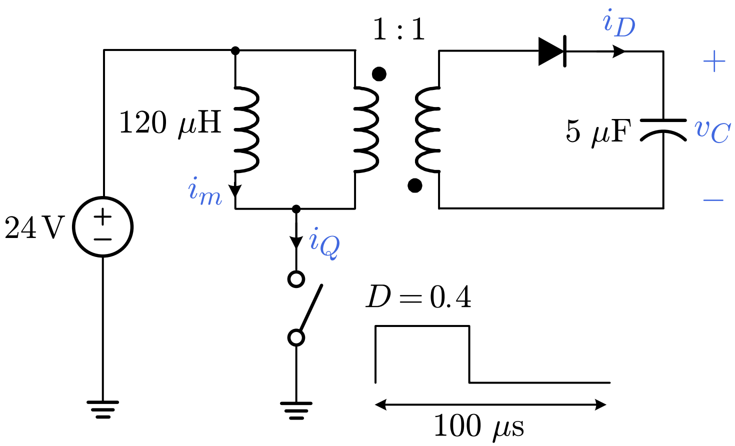


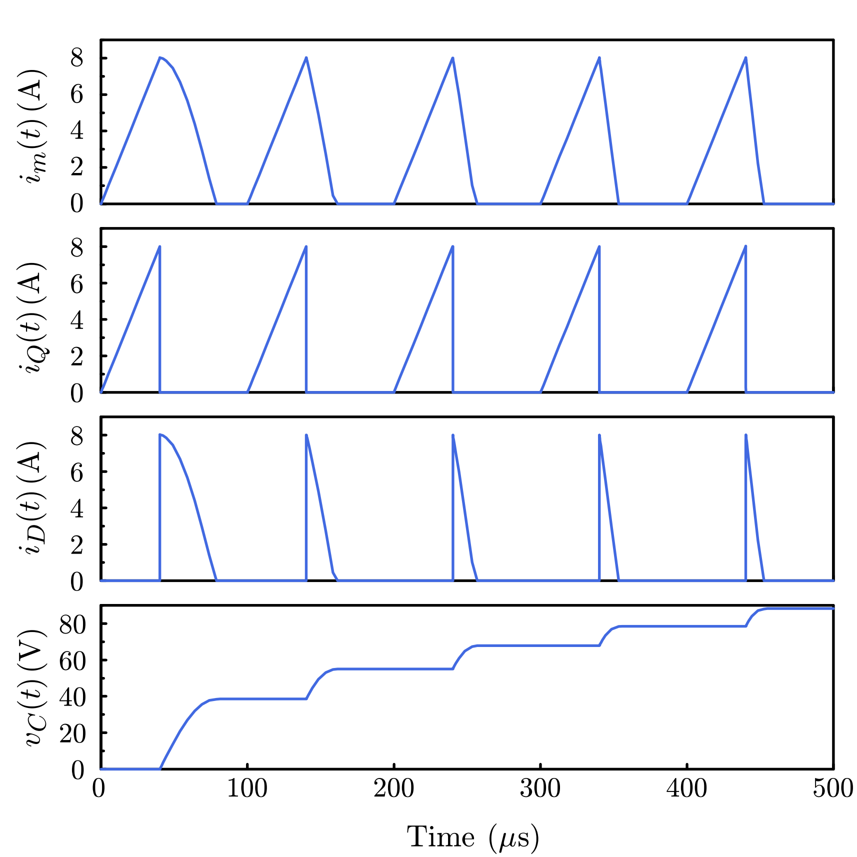
Circuit Waveforms



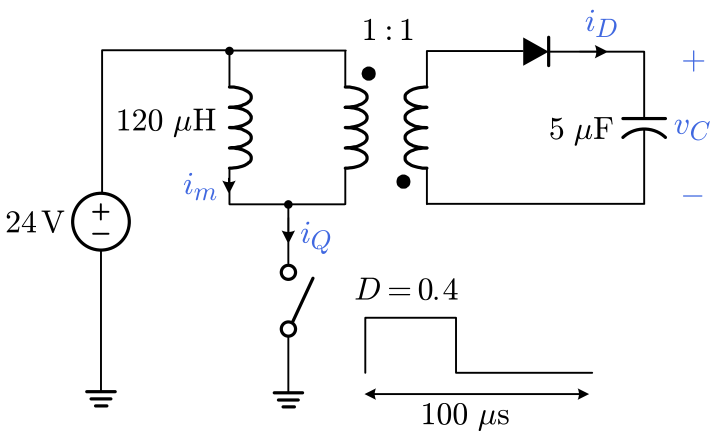
- The magnetizing current i_m increases linearly during the energy build-up period, but it decays in a nonlinear fashion in the energy transfer period.
- Duration of the energy transfer period sucessively diminishes as the operational cycles proceeds.
- The incremental increase in the capacitor voltage v_C becomes smaller as the operational cycle proceeds.

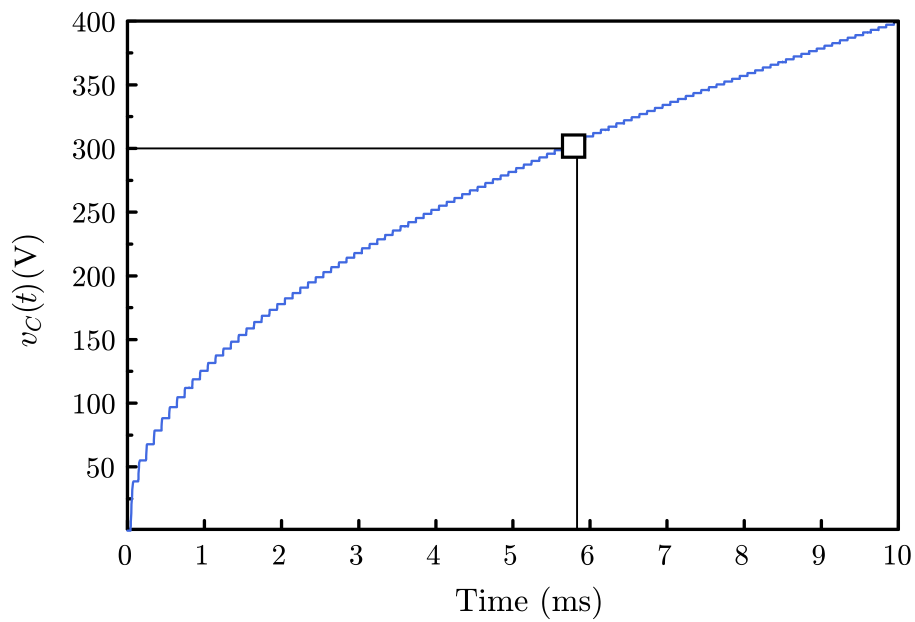
Example of Capacitor Charging Circuit





Example of Capacitor Charging Circuit





- Energy balance condition

- Total time required for charging V_C

- Total time required for charging $V_C = 300$ V