Pulsed Power system

⓪* Prerequisite courses:

Electric Circuits.

Engineering Mathematics / Phys Mathematics (ODE)

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②* No office hour, please feel free to stop by my office whenever my door is open & nobody is in my office. Or You may email me to schedule a meeting.

③* class time: 9:10 ~ 12:00 with 10 mins break

→ 9:10 ~ 11:30 English ~~Chinese~~

11:30 ~ 12:00 Mandarin for Q&A

④*. Assignments: 70% → No roll call.

Presentations: 30%

⑤* References: Pulsed power systems by H. Bluhm.

Circuits analysis by Cunningham and Stuller

* Additional References:

Pulsed Power by Gennady A. Mesyats

J. C. Martin on Pulsed Power

* Class material: myweb.ncku.edu.tw/~pchang

* Course Outline:

- Introduction to pulsed-power system. - (9/14) → 9/21.
- Review of circuit analysis - 9/21. ← HW. of KCL solvents

장2. Static and dynamic breakdown strength of dielectric material. - 9/28, 10/5

- Gas. → avalanche, townsend condition, paschen Law.
  * HW?
- Liquid
- Solid.

장3 Energy storage. 10/12 - 10/19.

- pulsed discharge capacitors
- Marx Generators. ← HW. of explaing Marx
- Inductive energy storage.

장4 Switches. 10/26 - ~~11/2~~. 11/9 ← ~~calculating capacitors~~ solving poisson's eq.

- Closing switches → gas switches
- Opening switches →

장5 Pulse-forming networks ~~11/9~~; ~~11/16~~ 11/23
11/16

- Transmission lines
- RLC Networks

장6 Pulse transmission and transformation ~~11/23~~ - ~~11/30~~ 12/7
11/30

- self-magnetic insulation in Vacuum lines
- pulse transformers
- High voltage power supply
- Transformation lines

§7. Power and voltage adding ~~[illegible]~~ 12/14

- Adding of power
- voltage adding

§9. Diagnostics 12/21 . 12/28.

- Electromagnetic-Field sensors
  - Capacitive sensor
  - Inductive
- Current-viewing resistors (CVRs)
- Current measurements based on Faraday Effect.
- E-field - - - - - - - - Electro-optic effects.
- Magnetic ion energy analysers
- Vacuum voltage monitors

§10. Applications of pulsed-power system 1/4

§

Introduction to pulsed-power system

* Pulsed power is a scheme where stored energy is discharged as electrical energy into a load in a short pulse or ~~as~~ short pulses with a controllable repetition rate.

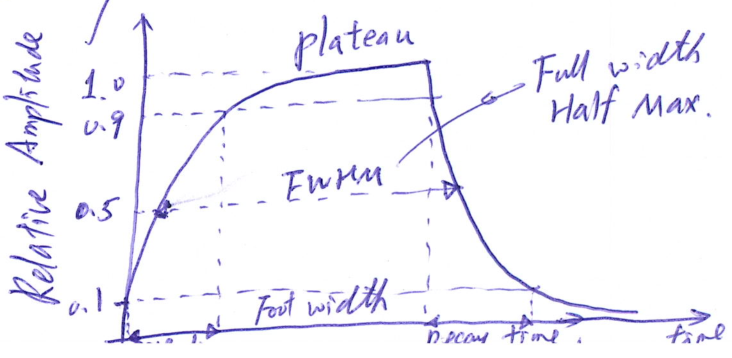
* Example of pulsed power in daily life:
  - Driven piles
  - Hammer.
  - making ~~sticky~~ rice cake. → great example of controlllable repetition rate. short pulses with a controllable repetition rate.

* Pulsed power in general: — $P \sim 10^9 W$ (1 GW) & $E \gtrsim kJ$

  The highest energy and power that have been achieved in a single pulse are in the order of 100 MJ & few hundred TW, respectively.

  — V: 10 kV ~ 50 MV
    I: 1 kA ~ 10 MA.

* A pulse is characterised by its shape, i.e., by its rise ~~time~~ & fall times and by the duration and flatness of its plateau region



- Pulse rise time – the time it takes the voltage to rise from 10% to 90%.

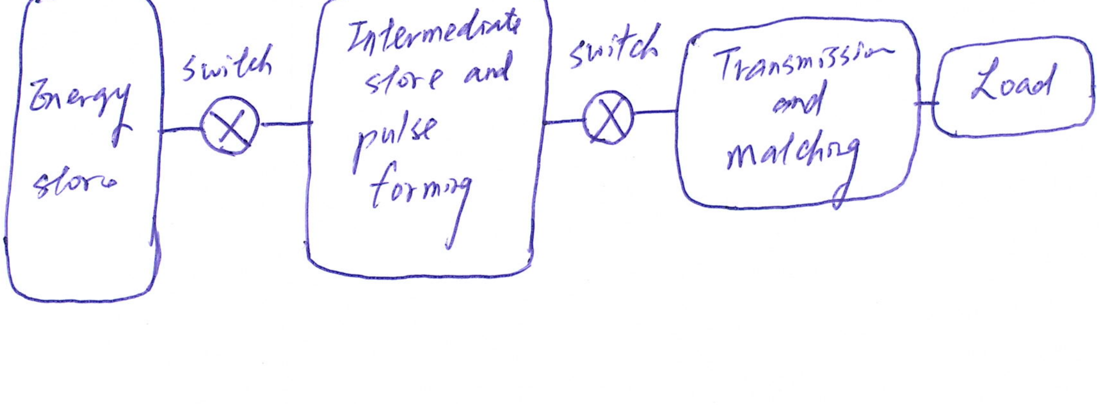
- pulse fall time / decay time – . . . . fall 90% to 10%.

- Both the fall and the rise time of a pulse depend on the evolution of the "Load impedance," which in most cases varies with time.

- pulse duration – no unique definition.
  - ↳ FWHM
  - ② ~~Sometimes~~ It is defined as the duration at 90% of the peak amplitude.
  - Flatness of the plateau region is an important requirement for driving some ~~for~~ loads, such as Pockels cells.

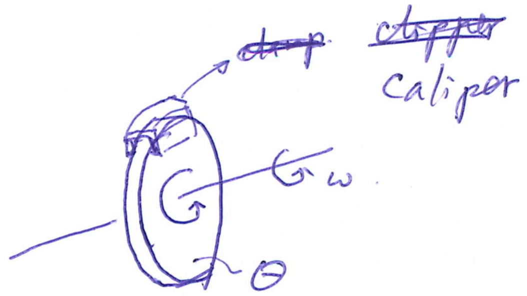
- A ~~general~~ generator scheme for the production of high-power electrical ~~pl~~ pulses is always based on an energy store that is charged slowly at a relatively low charging power and ~~by~~ is discharged rapidly by acting a switch.

- To achieve the desired power magnification factor and to shape the pulse, the above process can be repeated several time.



* The energy can be stored either chemically, mechanically, or electrically. P6.

Ex: Machenical energy:



$$W_{kin} = \frac{1}{2}\Theta\omega^2$$

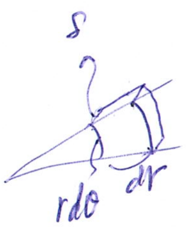
moment of inertia (Θ) — angular frequency (ω)

For a massive cylinder: $\Theta = \frac{1}{2} M r^2$ (M: mass, r: radius)

$$\Rightarrow W_{kin} = \frac{1}{2}\cdot\frac{1}{2} M r^2 \cdot \omega^2$$

$\Rightarrow$ Stored energy density: ~~W_{kin}~~ $w = \frac{W_{kin}}{M} = \frac{1}{4} r^2 \omega^2$

- The ultimate energy density is limited by the tensile strength of the material used to construct the rotor.



$$d\Sigma = \frac{dF}{A} = \frac{(rd\theta\, s\, dr\, \rho)\cdot r\omega^2}{rd\theta\cdot s} = \rho\omega^2 r\, dr$$

$$\Sigma = \int_0^R \rho\omega^2 r\, dr = \frac{1}{2}\rho\omega^2 R^2$$

$$\Sigma = \rho\,\omega_{max}^2 \frac{r^2}{2}.$$

Σ: tensile strength

for a stainless steel cylinder or radius 1m.

$\omega_{max} = 400$/sec.

AISI 302 stainless steel

$\Sigma = 520 / 860$ MPa (yield strength / ultimate tensile strength)

$\rho = 8.19\ g/cm^3 = 8190\ kg/m^3$

$$\Rightarrow \omega = \sqrt{\frac{2\Sigma}{\rho r^2}} = \sqrt{\frac{2\times 860\times 10^6}{8190\times 1}} = 458 \sim 400/$$

$$w_{kin} = \frac{1}{4} r^2\omega^2 = \frac{1}{4}\times 1^2\times 400^2 = 4\times 10^4\ J/kg$$

High strength alloy ASTM A514 steel

$\rho = 7.8\ g/cm^3$. $\Sigma = 690 / 760$ MPa (yield strength / ultimate tensile strength)

$$\omega = \sqrt{\frac{2\times 690\times 10^6}{7800\times 1^2}} = 420 \sim 400/sec$$

$$w_{kin} = \frac{1}{4} r\omega^2 = \frac{1}{4}\times 1\times 400^2 = 4\times 10^4\ J/kg = 3.1\times 10^8\ J/m^3$$

- The problem with mechanical storage is to release the energy in a sufficiently short time. p7.

→ Several electrical compression stages are needed in combination with the mechanical storage to achieve the desired power level.

Ex: Electrical energy can be stored either capacitively in an <u>electric field</u> or inductively in a <u>magnetic field</u>.

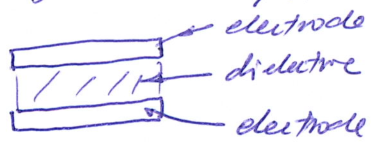
Ex1: Electric field:

$$W_e = \frac{1}{2}\varepsilon \cdot \varepsilon_0 E^2$$

for oilimpregnated paper: $\varepsilon = 6$, breakdown strength $E = 0.98 \times 10^8$ V/m

$$\Rightarrow W_e = \frac{1}{2} \times 6 \times 8.85 \times 10^{-12} \cdot (0.98 \times 10^8)^2 = 161 \text{ kJ/m}^3$$

- With the finite packing density:



$E_{re} = \frac{1}{2} C V^2$, $C = \varepsilon\varepsilon_0 \cdot \frac{A}{d}$

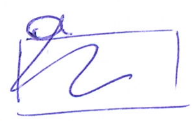
$\Rightarrow d \downarrow$, $E_{re} \uparrow$ → space is occupied by the electrode.

⇒ to estimate the energy storage in space

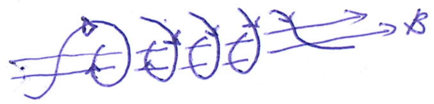
$$W_e' \approx \frac{1}{2} \times W_e \approx 80 \text{ kJ/m}^3$$

Ex2: Magnetic field:

$$W_B = \frac{B^2}{2\mu\mu_0}$$

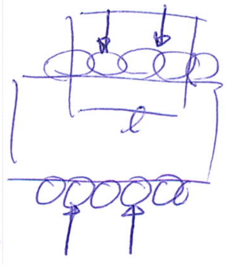


The maximum energy density is limited by the onset of melting at the conductor surface or by the mechanical strength of the storage inductor.



$$C_v \cdot \rho \cdot T = \frac{1}{2\mu_0} B^2 \vartheta$$

C_v: heat capacitor per unit mass; ρ: mass density; T: surface temperature; ϑ: a factor of order unity depending on the form of the pulse



$B \cdot l = \mu_0 N I$

$\Rightarrow B = \mu_0 n I \propto I$ resistor.

$\cancel{R}\ E = P \cdot t = I^2 \cdot R \cdot t \propto B^2 \cdot R \cdot t$

$\Rightarrow C_v \rho T = \frac{1}{2\mu_0} B^2 \vartheta \approx \frac{B^2}{2\mu_0}$ take $\vartheta = 1$

$$B \approx \sqrt{2\mu_0 \cdot C_v \cdot \rho \cdot T} = \sqrt{2 \times 4\pi \times 10^{-7} \times \frac{0.385\,J}{10^{3}\,kg \cdot K} \times 8960 \times (1085-25)}$$

Copper: $C_v = 0.385\ J/g \cdot K$ $= 96\,T \approx 100\,T$

melting: T: 1085 °C.

$\rho = 8.96\ g/cm^3 = 8960\ kg/m^3$

$P_B \leq \Sigma$ — yield strength $\Sigma = 70$ MPa for Cu.

$\Rightarrow \frac{B^2}{2\mu_0} \Rightarrow B \leq \sqrt{2\mu_0 \Sigma} = \sqrt{2 \times 4\pi \times 10^{-7} \times 70 \times 10^{6}}$

$= 13\,T$

$\cancel{\Rightarrow W_B = \frac{1}{2}\mu\mu_0 B^2 = \frac{1}{2} \times 4\pi \times 10}$ $\Rightarrow w_B = \frac{1}{2}\frac{B^2}{\mu\mu_0}$

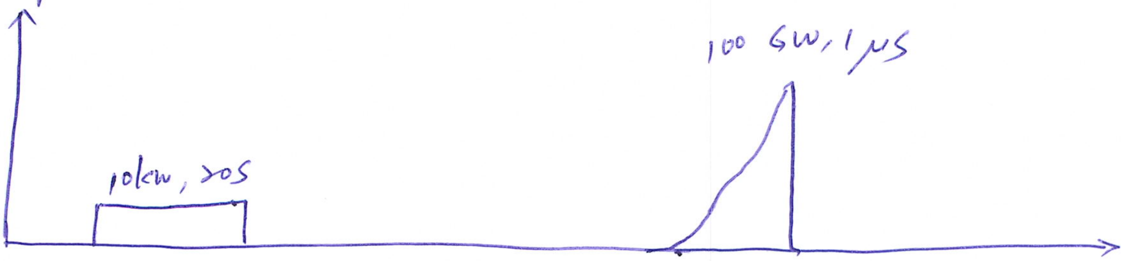
$\cancel{\Rightarrow W_B = \frac{1}{2}\mu\mu_0 B^2 = \frac{1}{2}}$ $= \frac{1}{2}\frac{13^2}{4\pi \times 10^{-7}} = 6.7 \times 10^{7}\ J/m^3$

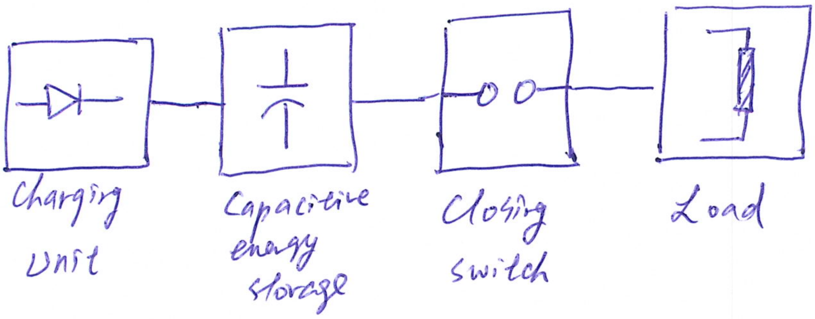
$= 67000\ kJ/m^3$

$\Rightarrow$ The energy density stored in a magnetic field can be about 2 orders of magnitude higher than that storable in an electric field!!

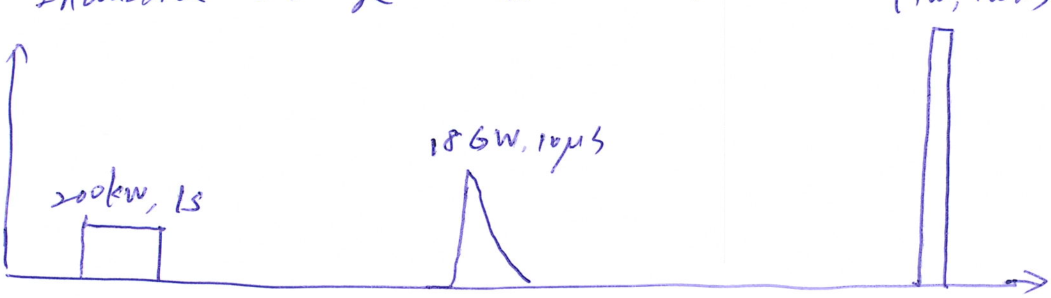
* Capacitive storage — requires one or more closing switches which remain open during charging and hold the charging voltage.
  - power multiplication is done by current amplification.
* Inductive storage — requires an opening switch. which is closed during charge-up, carrying a large current at this stage.
  - power multiplication is done by voltage amplification.

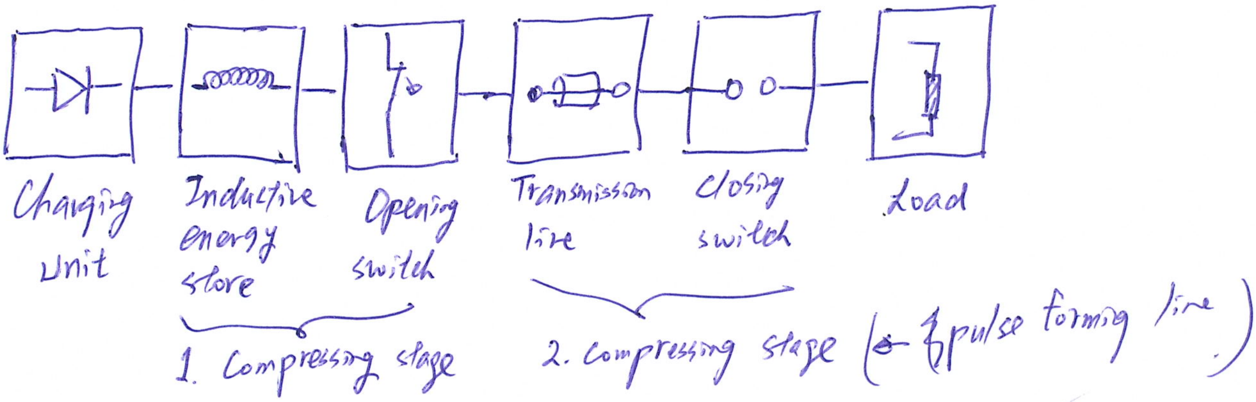
Capacitive storage $w_e = 10 \sim 80\ kJ/m^3$



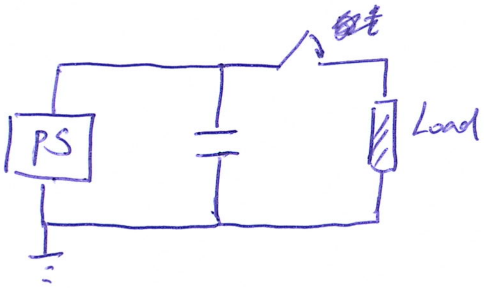


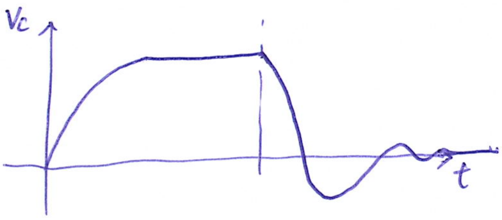
Inductive storage $w_m = 1 - 50\ MJ/m^3$

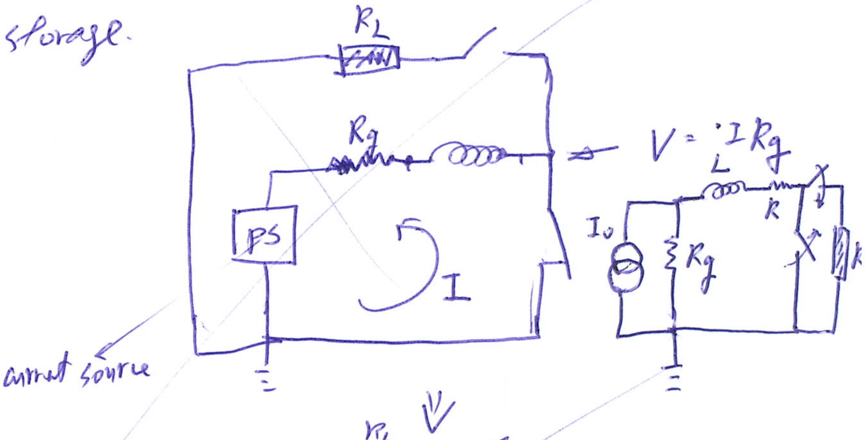


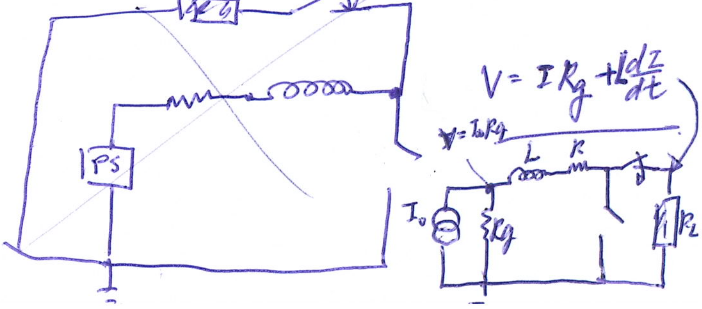


Example of Capacitive storage.









§ Review of circuit analysis

* Kirchhoff's Current Law.

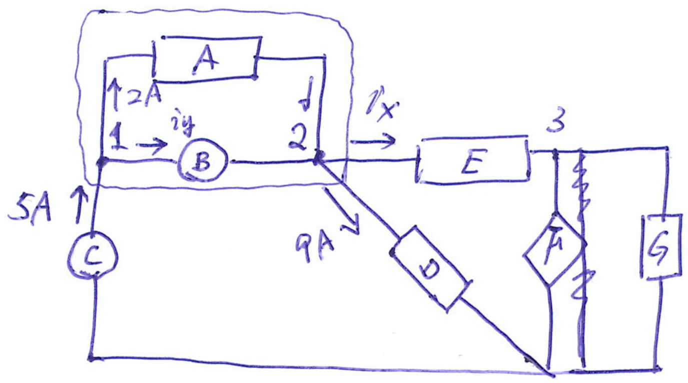
- At any instant in time, the algebraic sum of all currents leaving any closed surface is zero

$$i_1 + i_2 + \cdots \cdots + i_N = 0,$$

or in abbreviated notation:

$$\sum_{k=1}^{N} i_k = 0$$

where i_k is the k^{th} current of the N currents leaving the closed surfaces.



$i_y + 2 - 5 = 0$

$\Rightarrow i_y = 3\,(A)$

$-5 + i_x + 9 = 0$

$\Rightarrow i_x = -4\,(A)$

* Kirchhoff's Voltage Law.

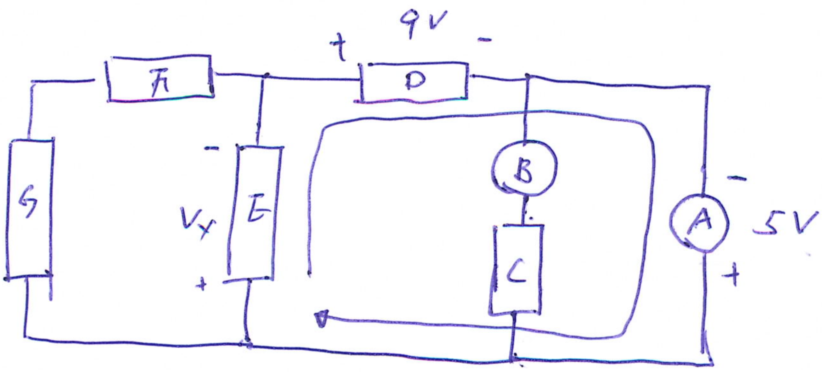
- At any instant in time, the algebraic sum of all voltage drops taken around any closed path is 0:

$$v_1 + v_2 + \cdots \quad v_N = 0.$$

or in abbreviated notation:

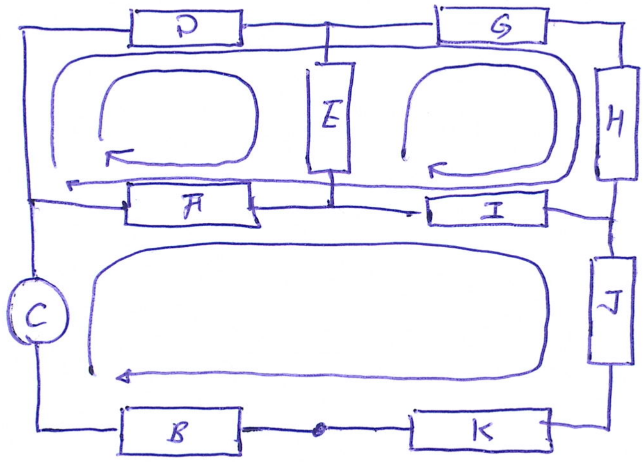
$$\sum_{k=1}^{N} v_k = 0$$

where v_k is the voltage drop, taken in the direction of the path along the k^{th} segment of the N segments in the closed path.

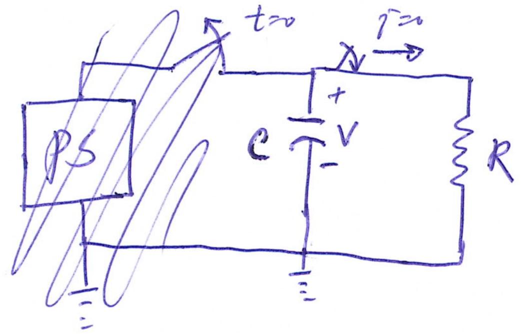


$$-V_x - 9 + 5 = 0 \quad \Rightarrow \quad \underline{V_x = -4\ V}$$

* Loops, Meshes, and Planar Networks



* Source-free RC circuit.



~~* Assume~~

⇒ Assume that the capacitor is fully charged to V_0.
At t=0, the switch is opened.

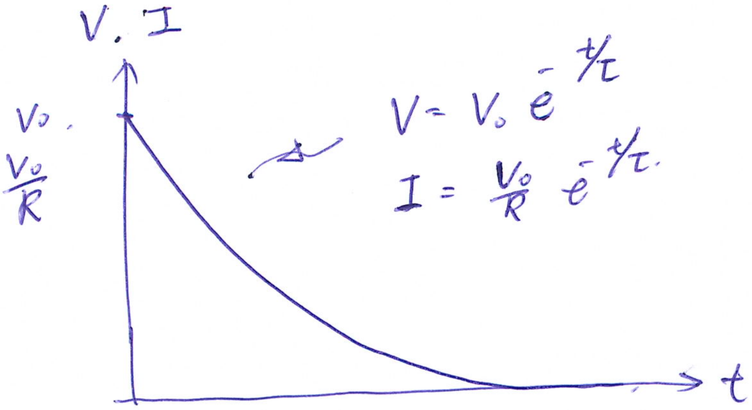
$V_c - IR = 0$ $\qquad I = \frac{dQ}{dt} = -C\frac{dV}{dt}$ $\qquad C = \frac{Q}{V}$

$\Rightarrow V_c + RC\frac{dV}{dt} = 0$ $\quad$ or $\quad \frac{dV}{dt} + \frac{1}{RC}V = 0$

$\Rightarrow \int_{V_0}^{V} \frac{dV}{V} = -\frac{1}{RC}\int_0^t dt \quad \Rightarrow \quad \ln\frac{V(t)}{V(0)} = -\frac{t}{RC}$

$\Rightarrow V(t) = V_0 e^{-t/RC} = \underline{V_0 e^{-t/\tau_c}}$ $\qquad \underline{\tau_c \equiv RC}$

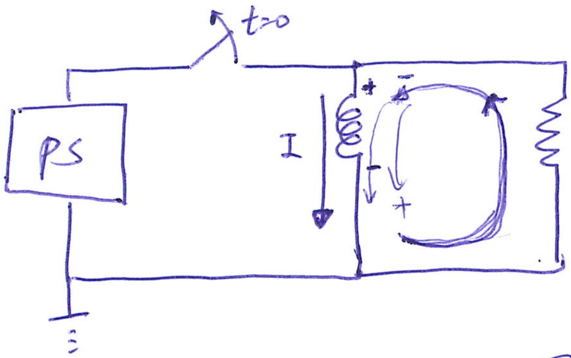
$I = -C\frac{dV}{dt} = +V_0 C\left(+\frac{1}{\tau}\right)e^{-t/\tau_c} = \underline{\frac{V_0}{R} e^{-t/\tau_c}}$



$V = V_0 e^{-t/\tau}$

$I = \frac{V_0}{R} e^{-t/\tau}$

* Source - free RL circuit



* Assuming the current is at steady state for $t \leq 0$, $I(0) = I_0$

At $t=0$, the switch is opened

$\cancel{V_L = IR + V_L = 0 \quad V_L = L\frac{dI}{dt}}$

$-IR - V_L = 0 \qquad V_L = L\frac{dI}{dt}$

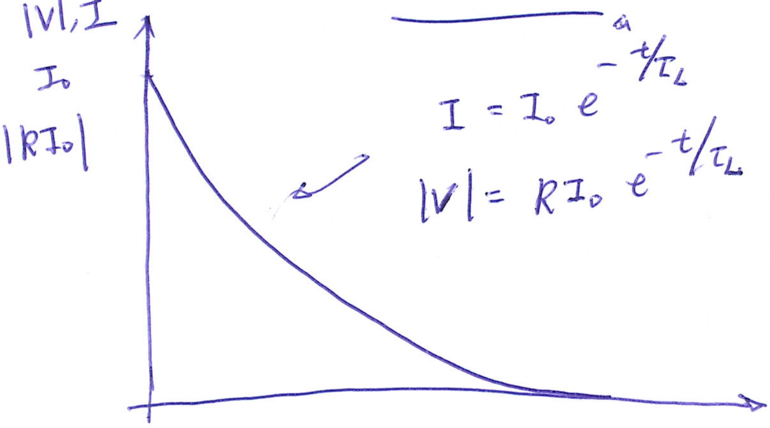
$\Rightarrow IR + L\frac{dI}{dt} = 0 \quad \Rightarrow \frac{dI}{dt} + \frac{R}{L} I = 0$

$\Rightarrow \int \frac{dI}{I} = -\frac{R}{L}\int dt \quad \Rightarrow \ln\frac{I(t)}{I(0)} = -\frac{R}{L}t \equiv -\frac{t}{\tau_L} \quad \tau_L = L/R$

$\Rightarrow I(t) = I_0 e^{-\frac{R}{L}t} = I_0 e^{-t/\tau_L}$

$V(t) = L\frac{dI}{dt} = L \cdot I_0 \cdot \left(-\frac{1}{\tau_L}\right) e^{-t/\tau_L}$, $\tau_L = L/R$

$= -RI_0 e^{-t/\tau_L}$



$I = I_0 e^{-t/\tau_L}$

$|V| = RI_0 e^{-t/\tau_L}$