Energy Storage Devices

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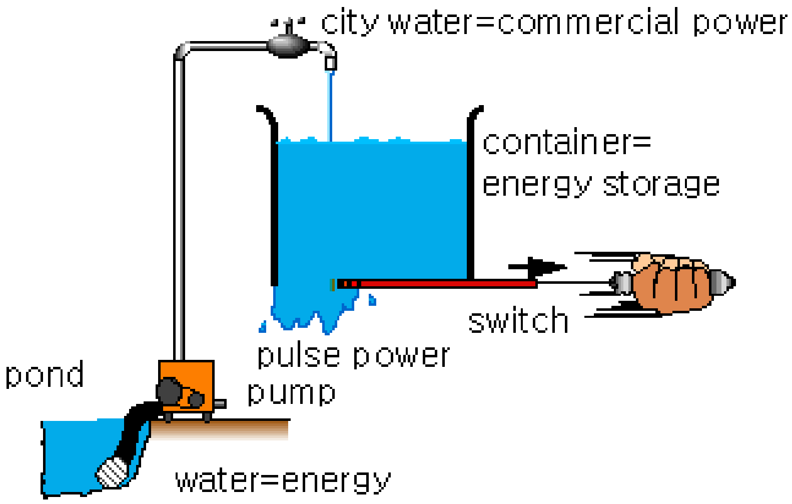
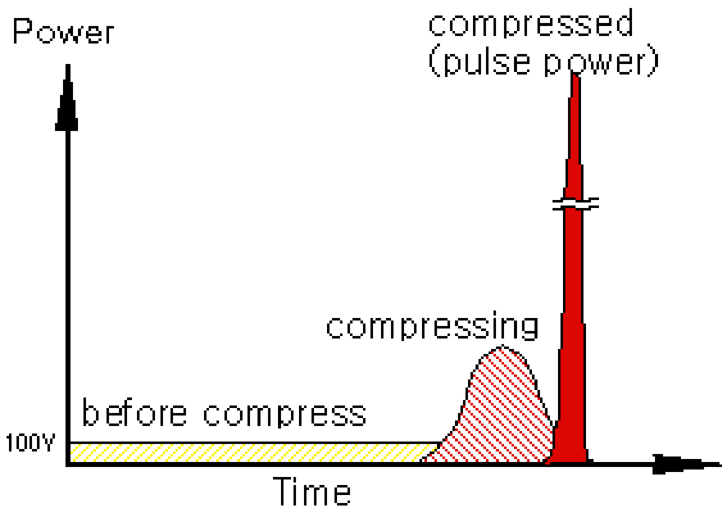
Kyoung-Jae Chung

Department of Nuclear Engineering

Seoul National University

Pulsed power: energy compression in time



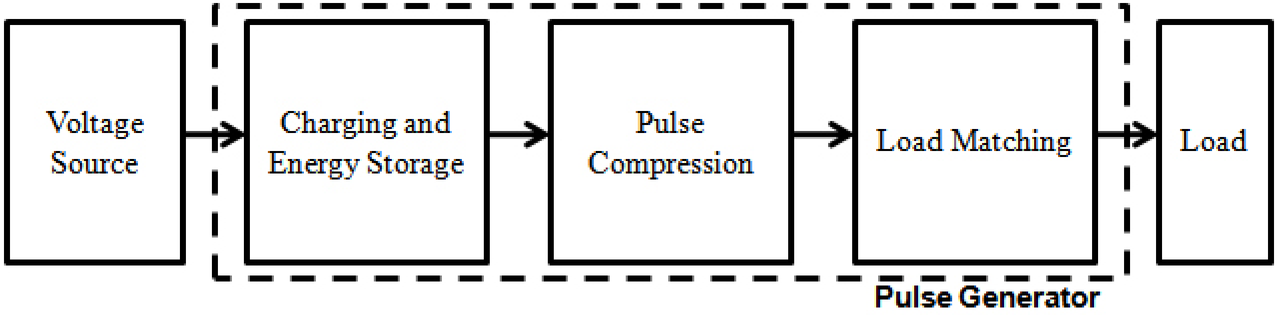


- **Pulsed Power Technology: the storage of electrical energy over a relatively long time scale and its release in a short duration to create very high power level**

- Example: E = 1 kW x 1 sec = 1 kJ
  P = 1 kJ / 1 us = **1 GW**

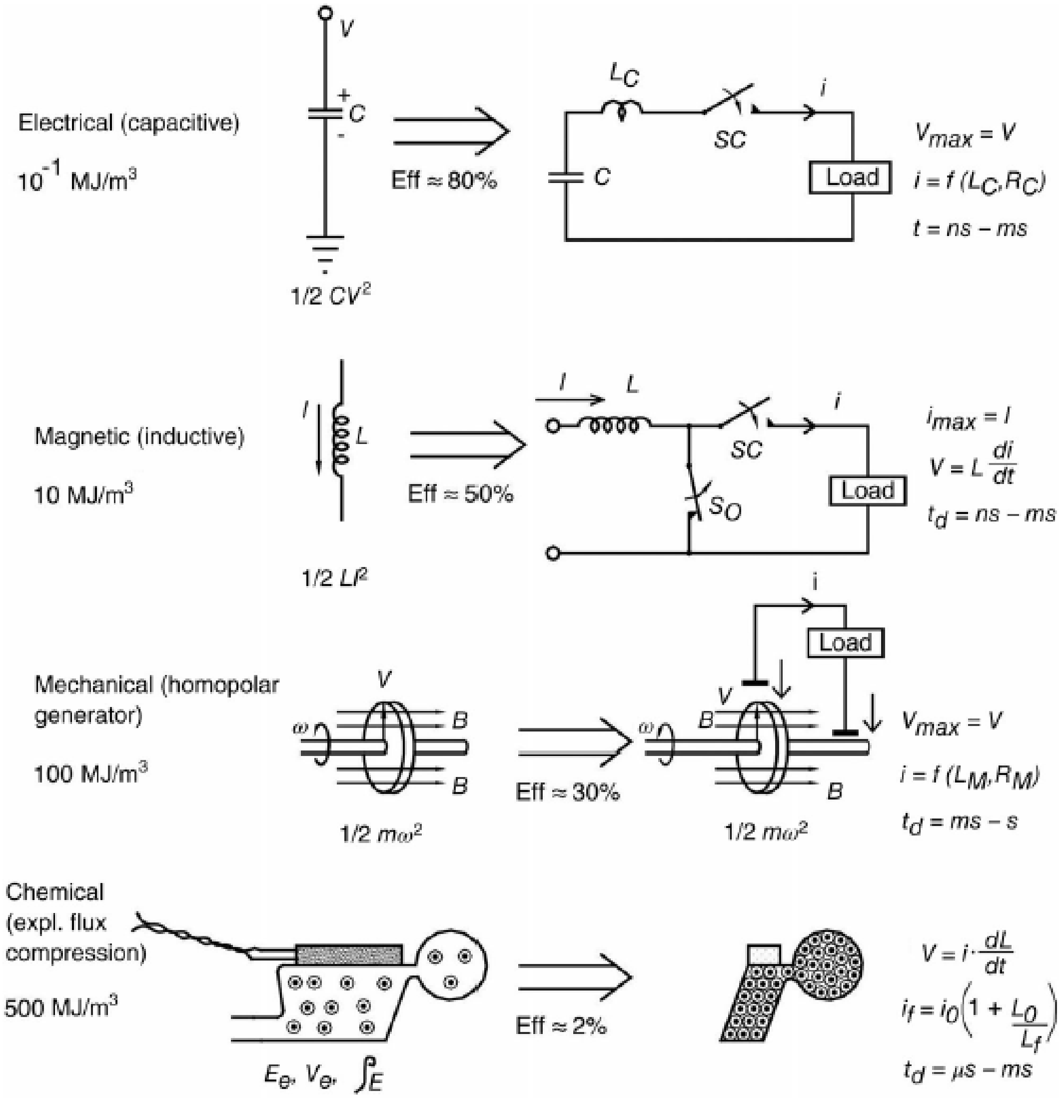
Pulsed power system

- Energy storage and fast switching play a key role in pulsed power technology.

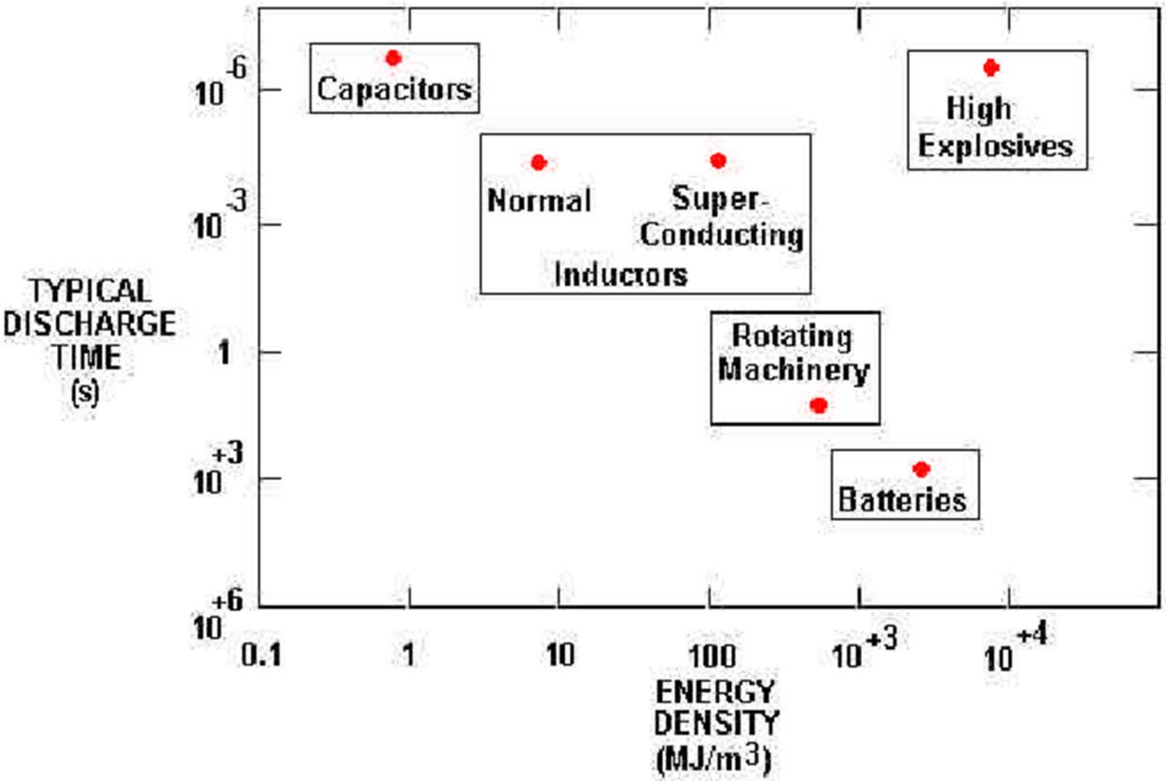


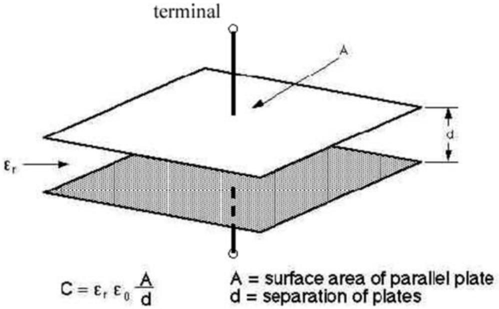
- Requirements of energy storage device for pulsed power application
  - High energy density
  - High breakdown strength
  - High discharge current capability
  - Long storage time (low rate of energy leakage)
  - High charging and discharging efficiency
  - Large power multiplication (ratio of power during charging to power during discharging)
  - Repetition rate capability and long lifetime
  - Low specific cost

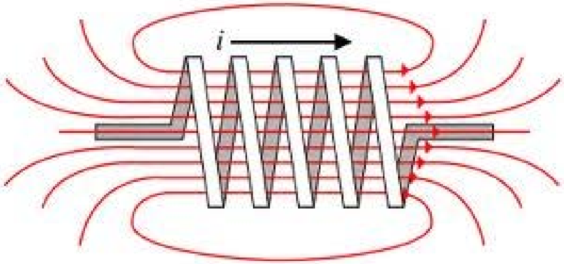
Various energy storage devices



Typical characteristics of energy storage devices







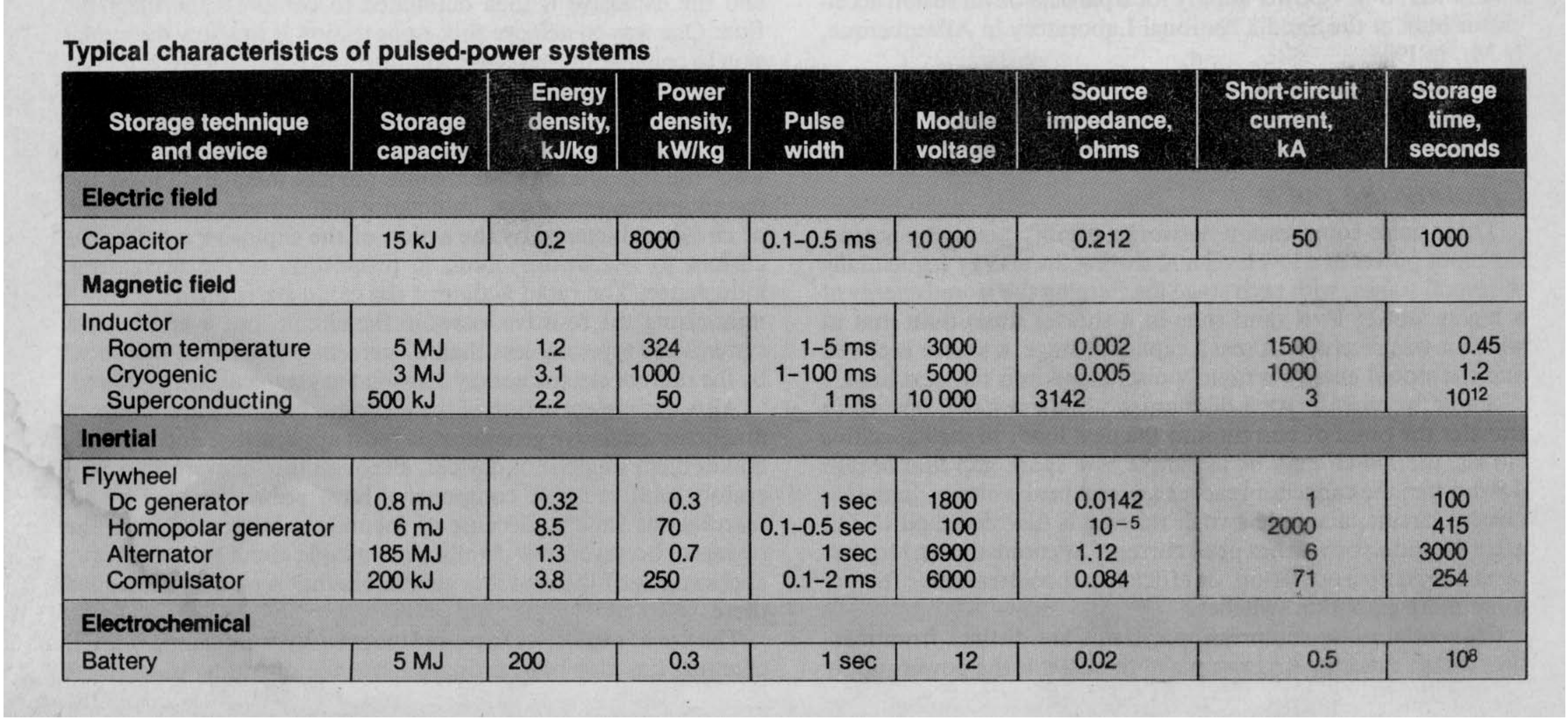
Consider

$$\varepsilon_r \approx 10$$
$$E \approx 10^8 \quad \text{V/m}$$
$$B \approx 10 \text{ T}$$
$$\mu = \mu_o$$

Then

$$\frac{1}{2}\varepsilon E^2 = 4.4 \times 10^5 \quad \text{J/m}^3$$
$$\frac{1}{2}\frac{B^2}{\mu_o} \approx 4 \times 10^7 \quad \text{J/m}^3$$

Typical characteristics of energy storage devices

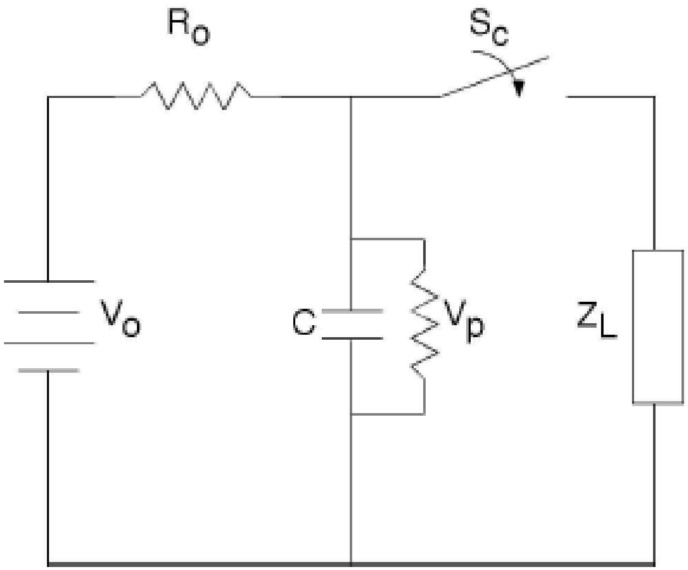


Typical characteristics of pulsed-power systems

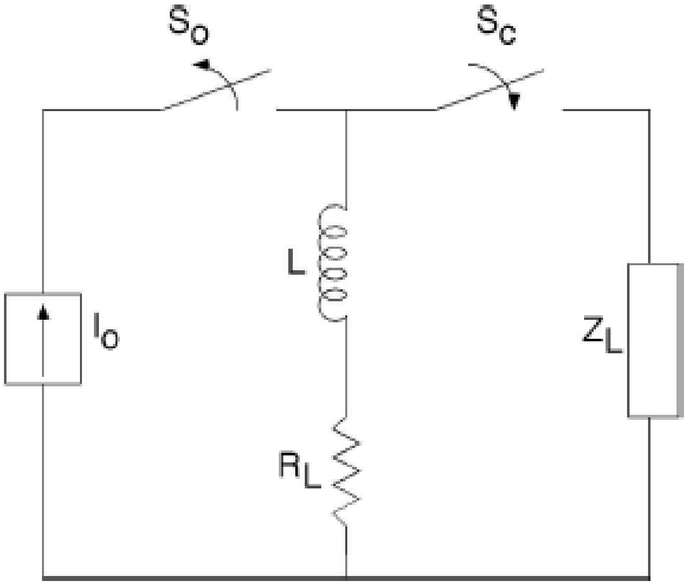
Storage technique and device	Storage capacity	Energy density, kJ/kg	Power density, kW/kg	Pulse width	Module voltage	Source impedance, ohms	Short-circuit current, kA	Storage time, seconds
Electric field								
Capacitor	15 kJ	0.2	8000	0.1–0.5 ms	10 000	0.212	50	1000
Magnetic field								
Inductor								
Room temperature	5 MJ	1.2	324	1–5 ms	3000	0.002	1500	0.45
Cryogenic	3 MJ	3.1	1000	1–100 ms	5000	0.005	1000	1.2
Superconducting	500 kJ	2.2	50	1 ms	10 000	3142	3	10^{12}
Inertial								
Flywheel								
Dc generator	0.8 mJ	0.32	0.3	1 sec	1800	0.0142	1	100
Homopolar generator	6 mJ	8.5	70	0.1–0.5 sec	100	10^{-5}	2000	415
Alternator	185 MJ	1.3	0.7	1 sec	6900	1.12	6	3000
Compulsator	200 kJ	3.8	250	0.1–2 ms	6000	0.084	71	254
Electrochemical								
Battery	5 MJ	200	0.3	1 sec	12	0.02	0.5	10^8

W. F. Weldon, IEEE Spectrum 22, 59 (1985)

Capacitive vs inductive circuits



Capacitive Energy Discharge Circuit



Inductive Energy Discharge Circuit

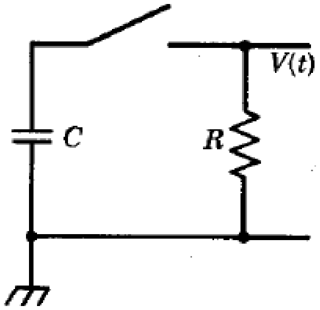
RC circuit

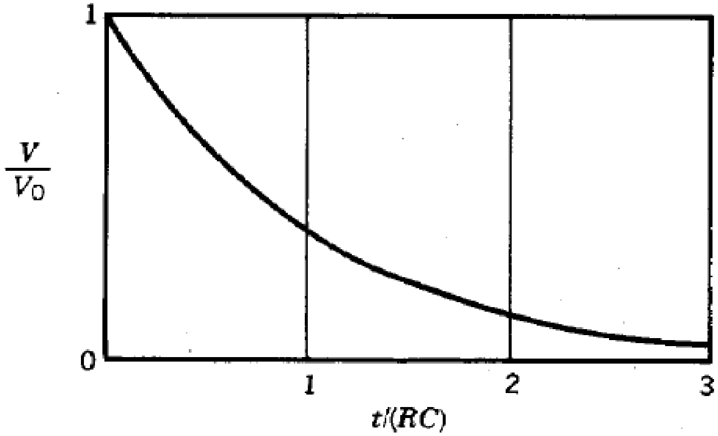
- This is the simplest model for a pulsed voltage circuit; electrical energy is stored in a capacitor and then dumped into a load resistor via a switch.

$$C\frac{dV}{dt}+\frac{V}{R}=0$$

$$\Downarrow$$

$$V(t)=V_0\exp\left(-\frac{t}{RC}\right)$$



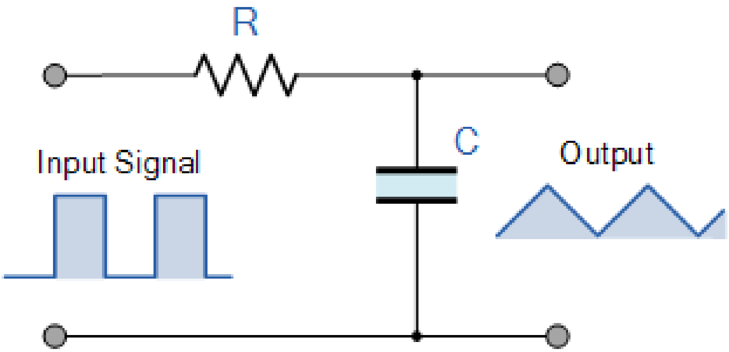


- Passive integrator (keep $V \ll V_{in}$ by keeping the product RC large)

$$I=C\frac{dV}{dt}=\frac{V_{in}-V}{R}\approx\frac{V_{in}}{R}$$

$$\Downarrow$$

$$V\approx\frac{1}{RC}\int V_{in}(t)dt$$



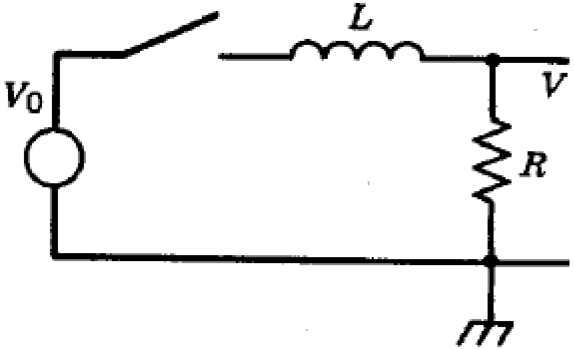
RL circuit

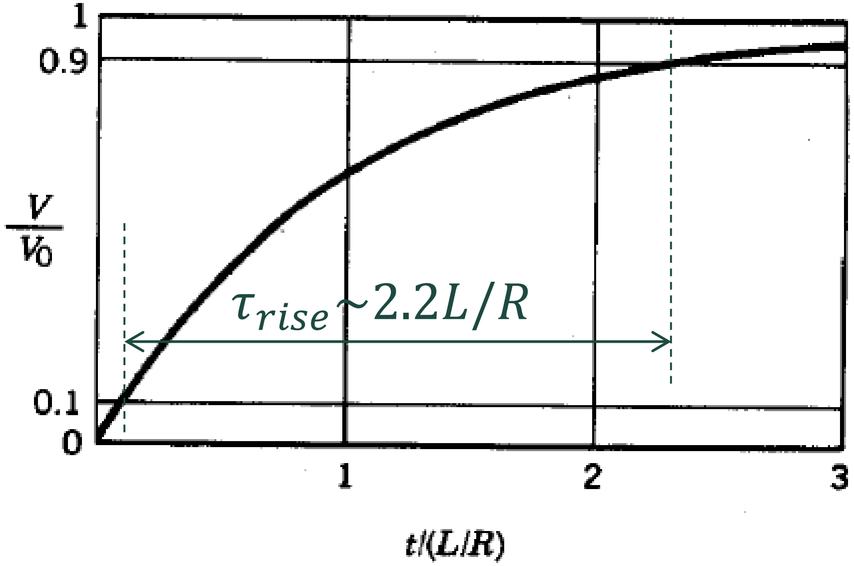
- Usually, we want a rapid rise time for power into the load. The time for initiation of current flow to the load is limited by the undesirable (or parasitic) inductance.

$$L\frac{di}{dt} + Ri = 0$$

$$\Downarrow$$

$$V(t) = V_0\left[1 - \exp\left(-\frac{t}{(L/R)}\right)\right]$$



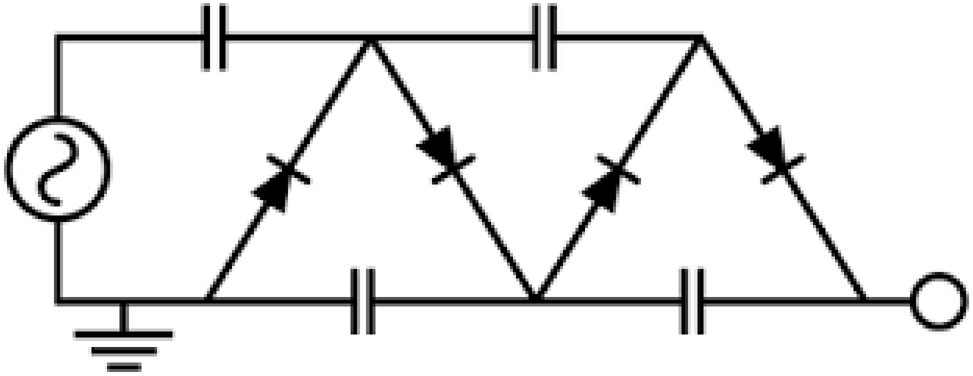


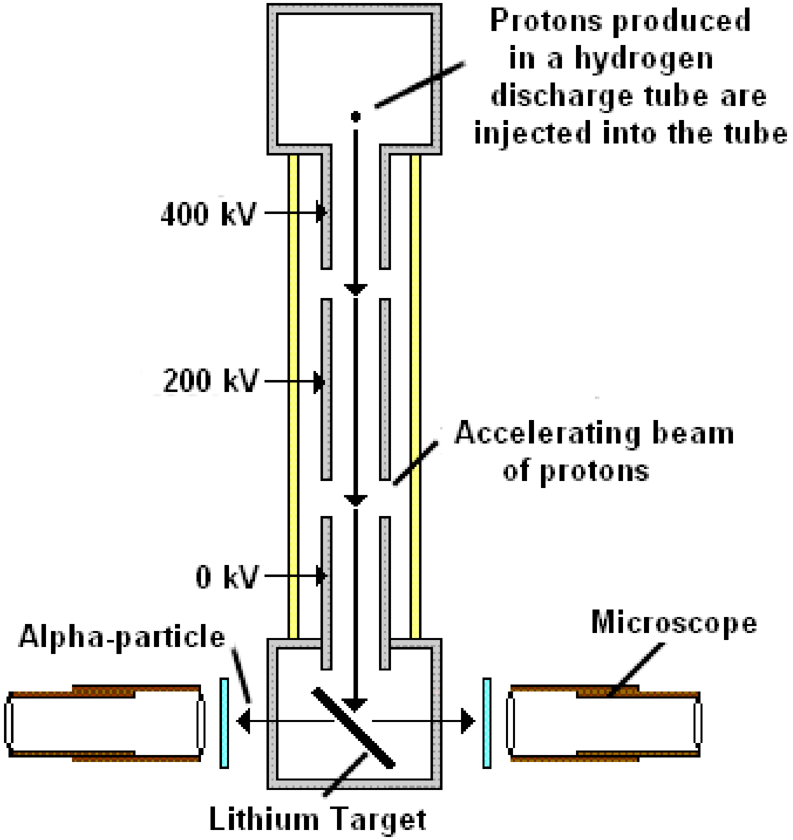
- The L/R time determines how fast current and voltage can be induced in the load.

Cockcroft-Walton's voltage multiplier

- The first nuclear disintegration by nuclear projectiles artificially produced in a man-made accelerator (1932).

$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \ (+17.3\ \mathrm{MeV})$$



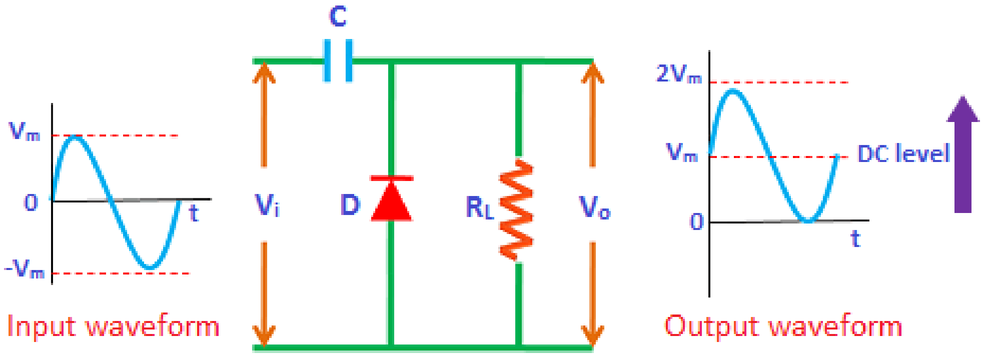


Cockcroft and Walton, Proc. Roy. Soc. A136, 619 (1932)
Cockcroft and Walton, Proc. Roy. Soc. A137, 229 (1932)

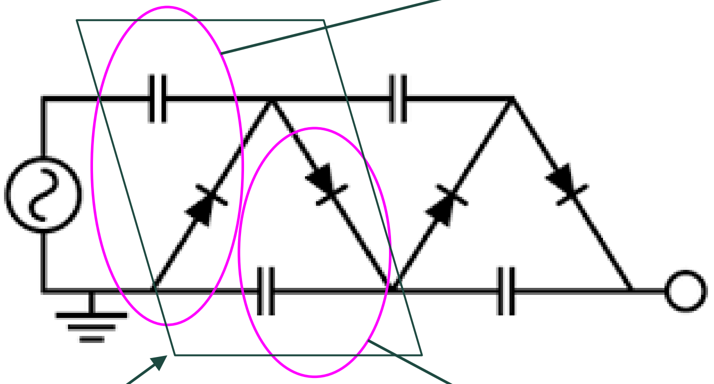
Analysis of Cockcroft-Walton's voltage multiplier circuit

- The voltage multiplier circuit is a combination of a clamping circuit and a peak detector circuit (rectifier circuit).

Clamping circuit
(positive clamper)



Positive clamper

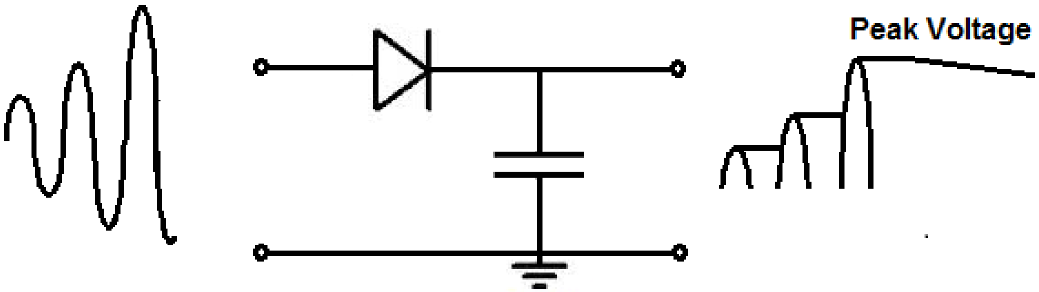


1 stage

$$V_{out} = 2NV_p = NV_{pp}$$

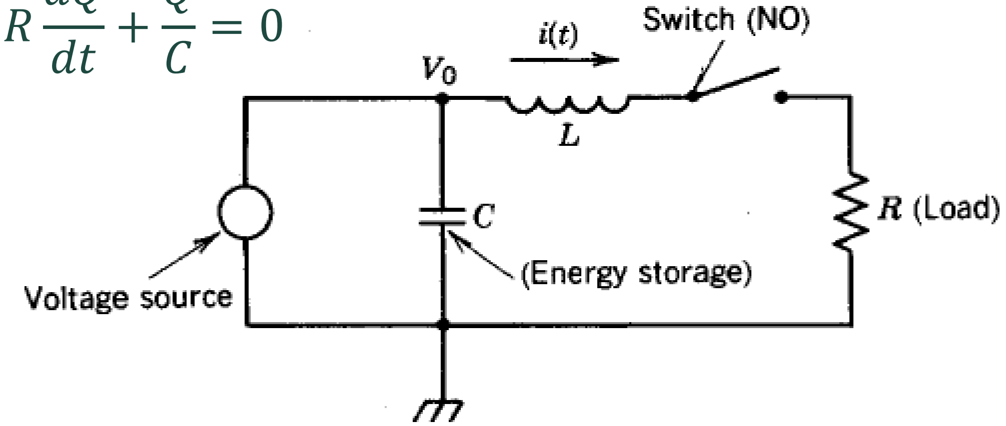
+

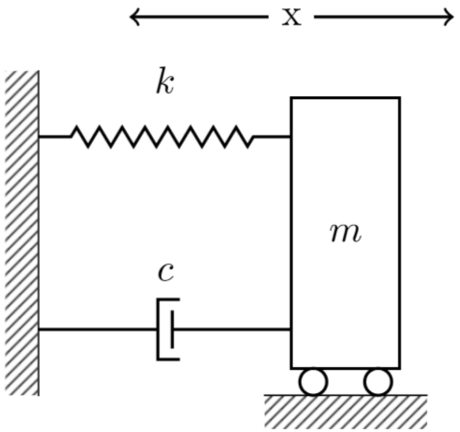
Peak detector circuit
(rectifier circuit)



RLC circuit

$$L\frac{d^2Q}{dt^2}+R\frac{dQ}{dt}+\frac{Q}{C}=0$$





$$\frac{d^2Q}{dt^2}+2\alpha\frac{dQ}{dt}+\omega_0^2Q=0 \qquad where, \qquad \alpha=\frac{R}{2L}, \qquad \omega_0=\frac{1}{\sqrt{LC}}$$

- Initial conditions: $Q(t=0)=CV_0,\qquad dQ/dt\,(t=0)=0$

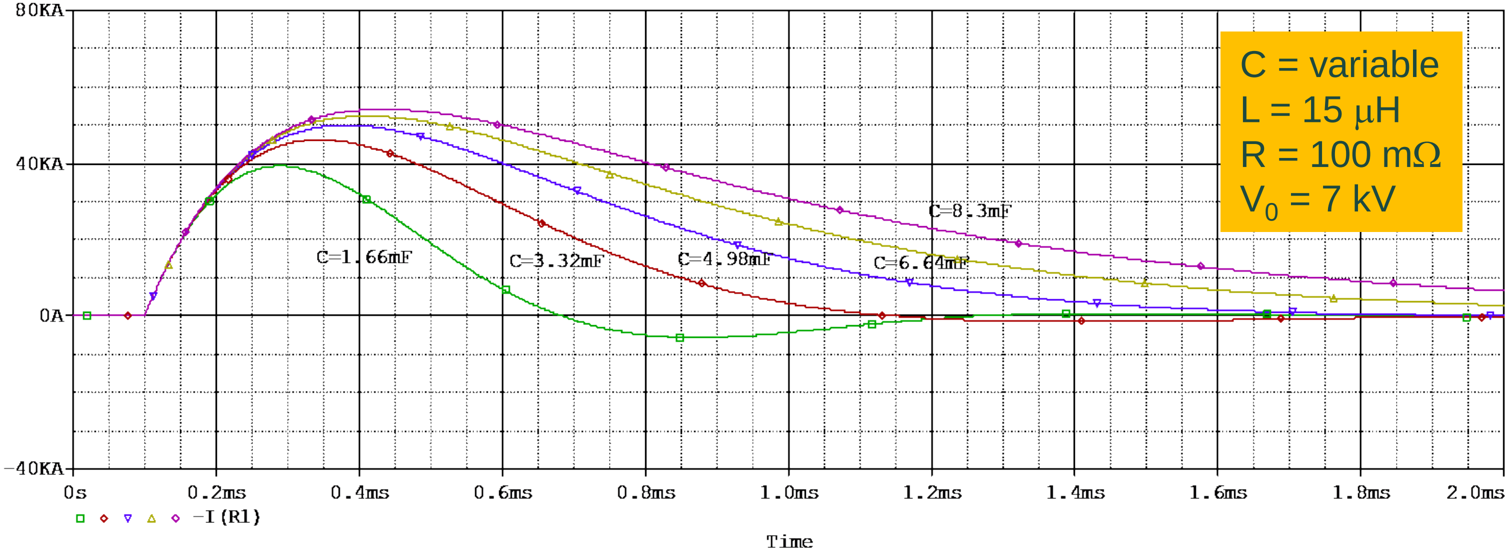
(1) Overdamping $\quad R>2\sqrt{L/C} \qquad i(t)=\dfrac{V_0}{\beta L}e^{-\alpha t}\sinh\beta t \quad (\beta^2=\alpha^2-\omega_0^2)$

(2) Critical damping $\quad R=2\sqrt{L/C} \qquad i(t)=\dfrac{V_0}{L}te^{-\alpha t}$

(3) Underdamping $\quad R<2\sqrt{L/C} \qquad i(t)=\dfrac{V_0}{\omega_d L}e^{-\alpha t}\sin\omega_d t \quad (\omega_d^2=\omega_0^2-\alpha^2)$

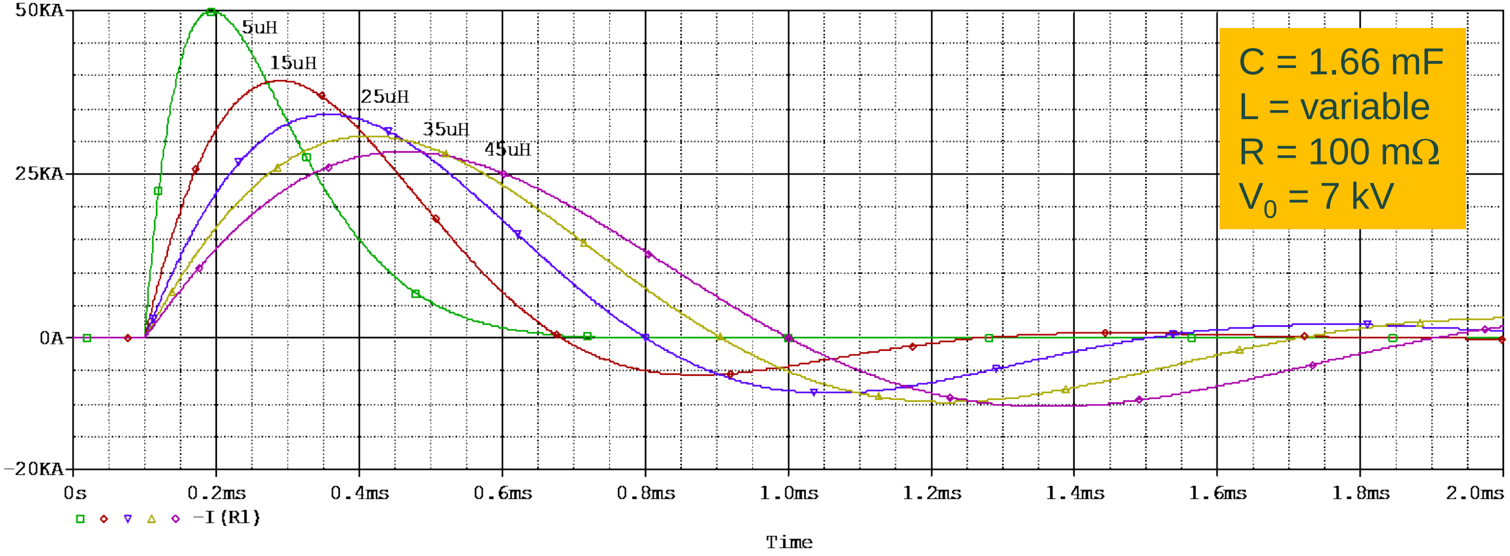
RLC circuit

- Variable C



C = variable
L = 15 μH
R = 100 mΩ
V_0 = 7 kV

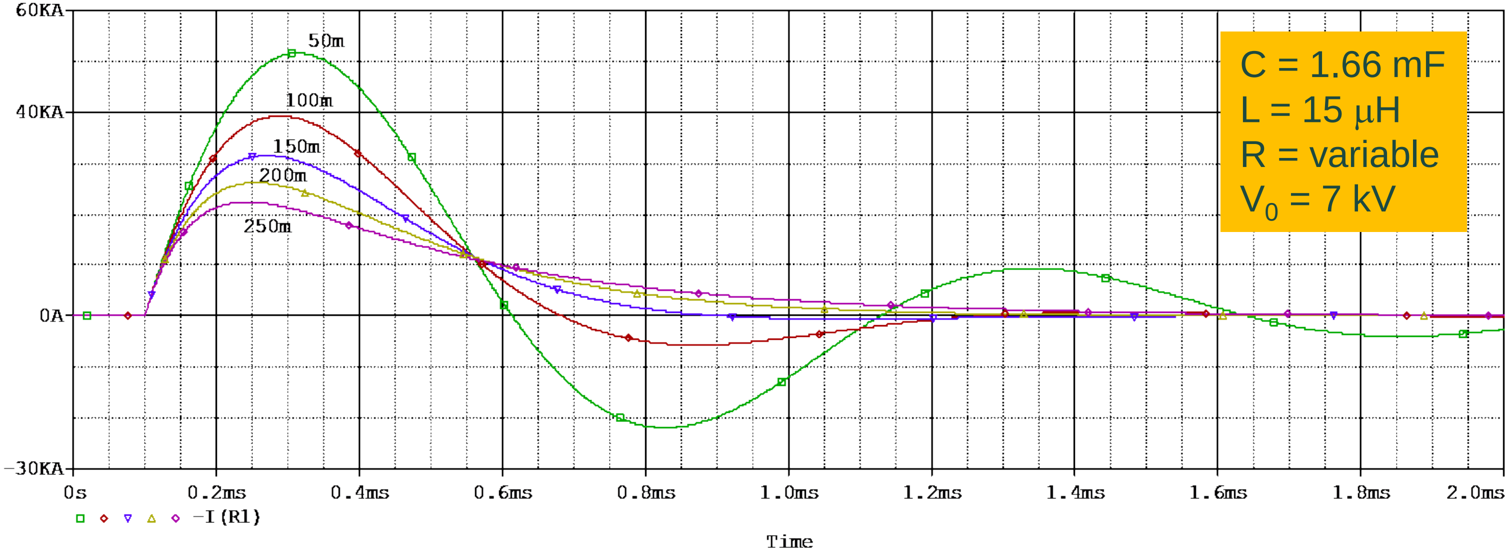
- Variable L



C = 1.66 mF
L = variable
R = 100 mΩ
V_0 = 7 kV

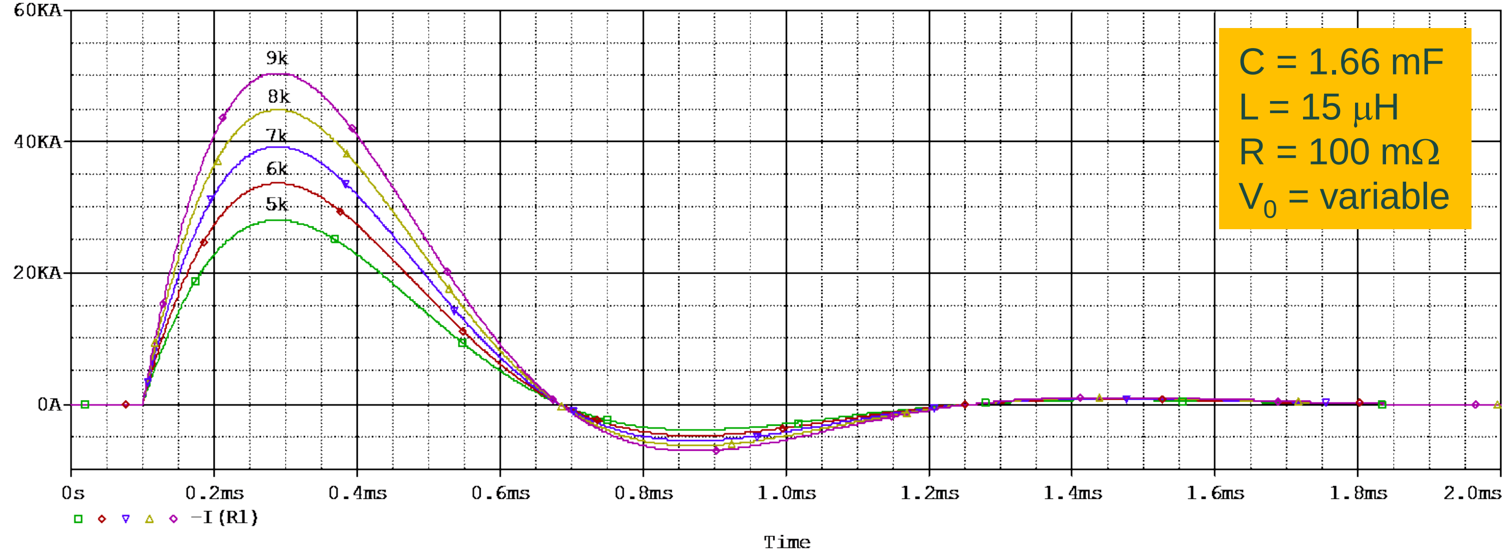
RLC circuit

- Variable R



C = 1.66 mF
L = 15 μH
R = variable
V_0 = 7 kV

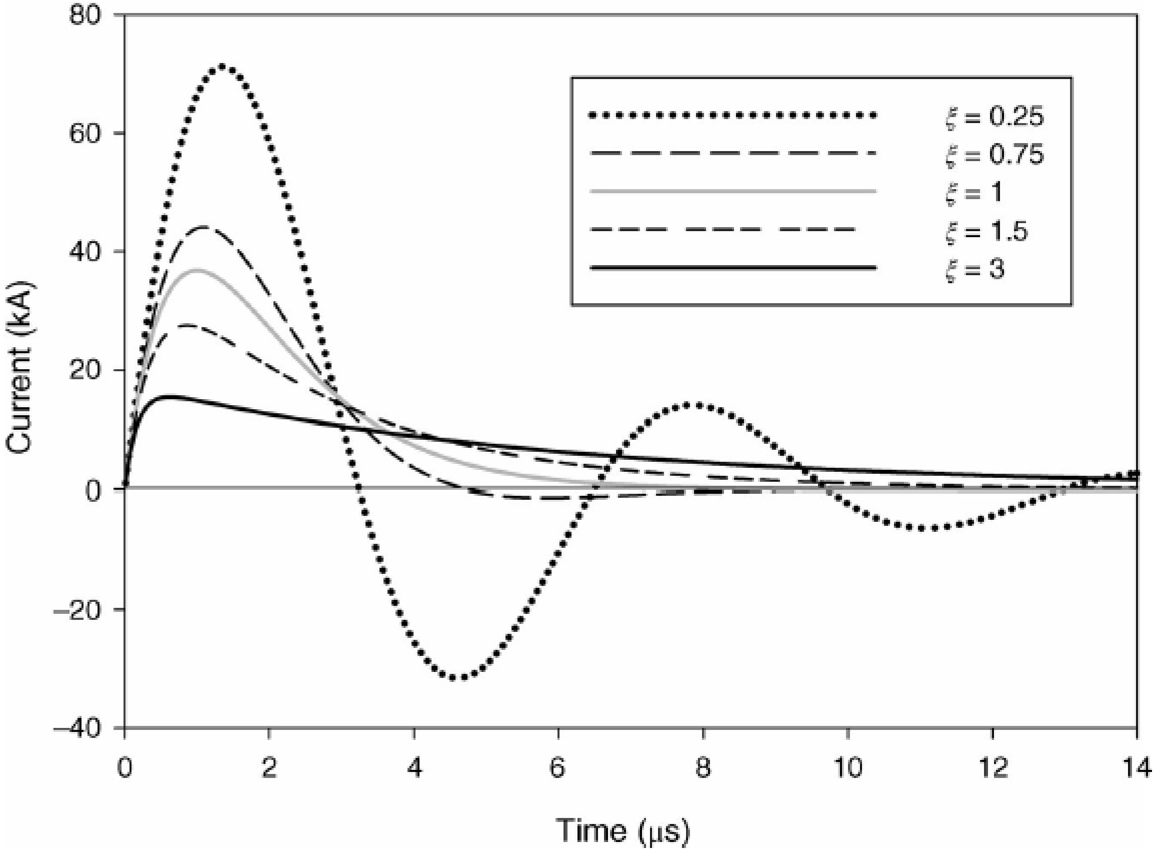
- Variable V_0



C = 1.66 mF
L = 15 μH
R = 100 mΩ
V_0 = variable

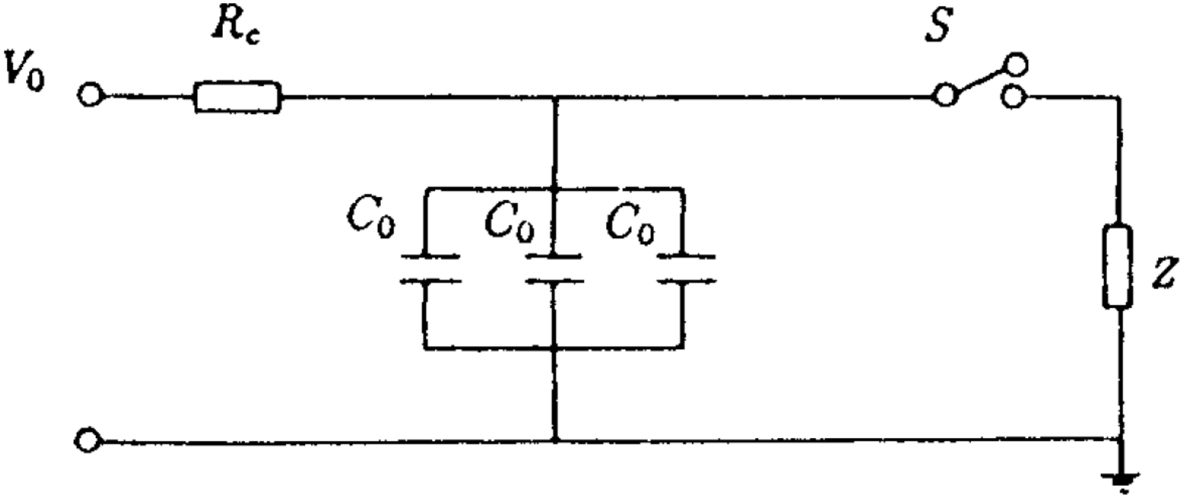
Comparison of circuit response

- The underdamped responses, where $\xi < 1$, have larger peak currents than the critically damped response and oscillatory behavior. Capacitor banks maybe designed to achieve these large peak currents and then use a crowbar switch to protect the circuit against the large voltage swings from the oscillations.



Capacitive circuit

- The capacitor bank can supply large current



R_c–Charging resistor

C_0–Storage capacitor

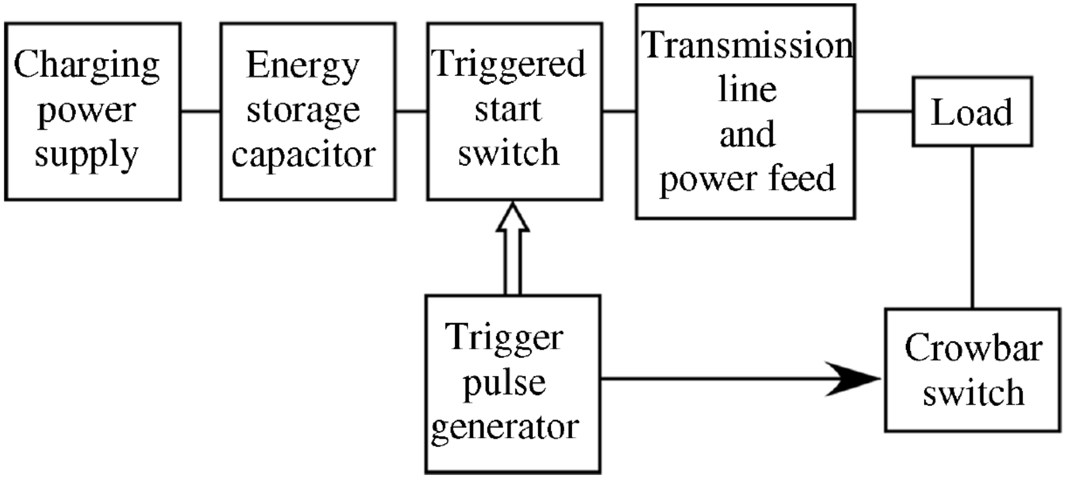
S–Discharge switch

Z–Load

V_0–Charging voltage

Circuit topology of energy storage capacitor bank

- A crowbar switch protects the capacitor from excessive voltage reversal. It may be self-breaking or externally triggered.



Charging power supply

Energy storage capacitor

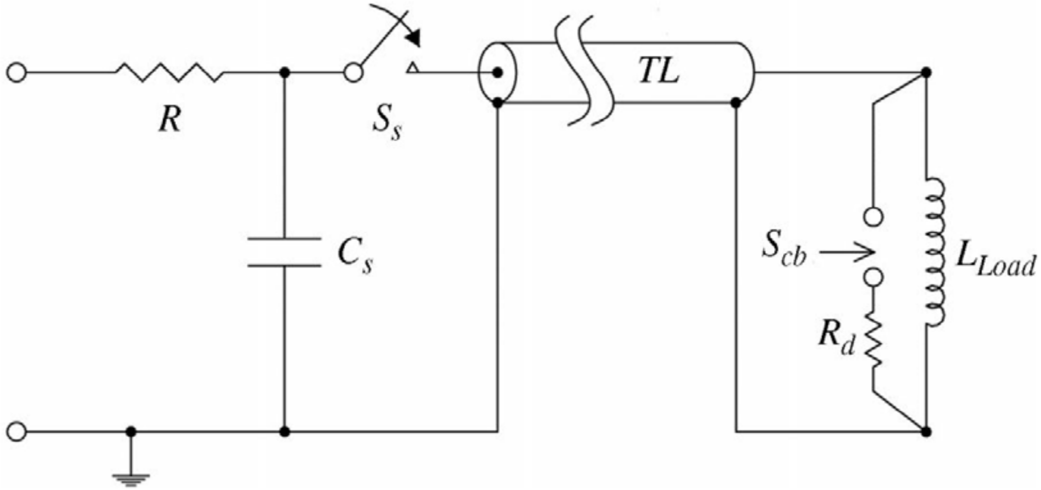
Triggered start switch

Transmission line and power feed

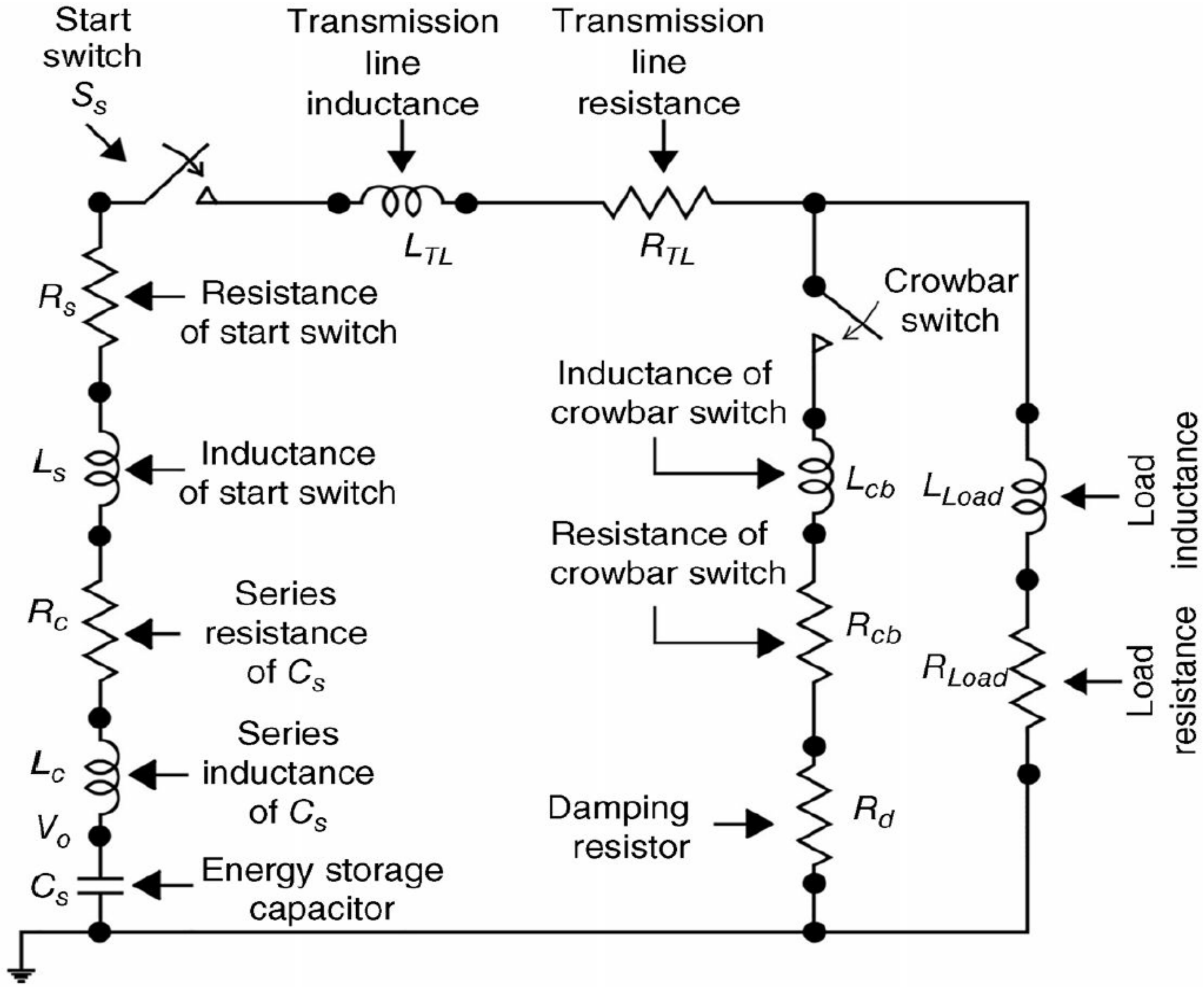
Load

Trigger pulse generator

Crowbar switch



Equivalent circuit of capacitive discharge system



Constant voltage charging

- The maximum current for a given maximum voltage and a power rating of the power supply is

$$I_{max} = \frac{P_s}{V_{max}}$$

- The minimum resistance value of a current limiting resistor is

$$R_{min} = \frac{V_{max}}{I_{max}}$$

- The voltage across the capacitor is

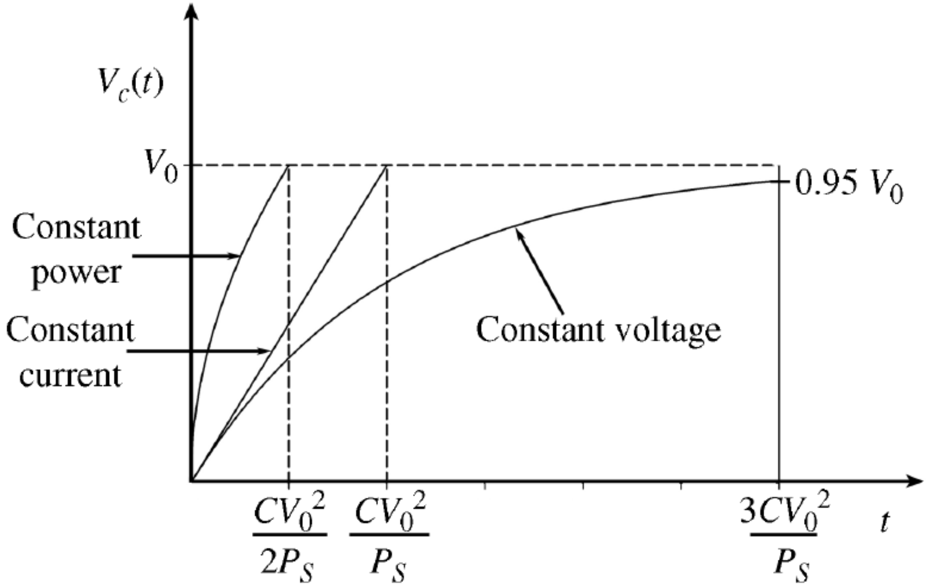
$$V_C(t) = V_0[1 - e^{-t/RC}]$$

- 99% charging time is

$$T_{ch} = 5RC = 5\left(\frac{V_0}{I_0}\right)C = 5 \times \frac{CV_0^2}{P_s}$$

- Charging efficiency

$$\eta = \frac{E_C}{E_{PS}} = \frac{E_C}{E_R + E_C} = \frac{(1/2)CV_0^2}{\int_0^\infty (V^2/R)dt + (1/2)CV_0^2} = \frac{(1/2)CV_0^2}{(1/2)CV_0^2 + (1/2)CV_0^2} = \frac{1}{2}$$



Constant current charging

- For a power supply with a power rating of P_s and a constant current of I_0, the charging rate of the capacitor can be calculated by

$$I_0 = C\frac{dV}{dt}$$

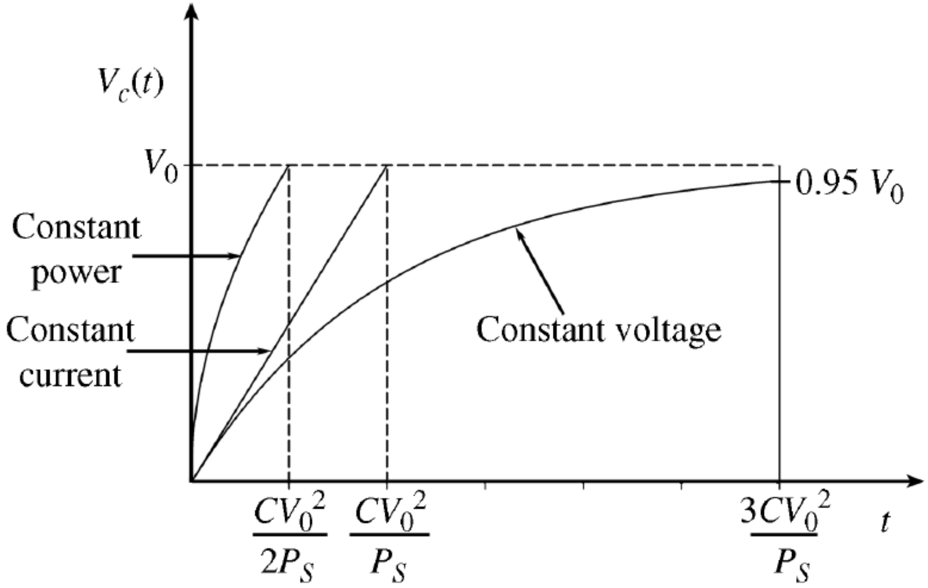
- The voltage on the capacitor at any time is

$$V_C(t) = \int_0^t \frac{I_0}{C}dt = \frac{I_0}{C}t$$

- The charging time is

$$T_{ch} = \frac{CV_0}{I_0} = \frac{CV_0^2}{P_s}$$

→ Five times faster than resistive charging



- A constant current mode of charging can be implemented by using active electronic components. Constant current power supplies are often specified in units of energy per time (kJ/s) and are commercially available.

Constant power charging

- For a constant power unit, the product between the capacitive voltage V_C and current I_C is a constant:

$$P_s = I_C(t) \cdot V_C(t) = \text{constant}$$

$$I_C(t) = C\frac{dV_C(t)}{dt} \quad \Rightarrow \quad CV_C(t)dV_C(t) = I_C(t)V_C(t)dt = P_s dt$$

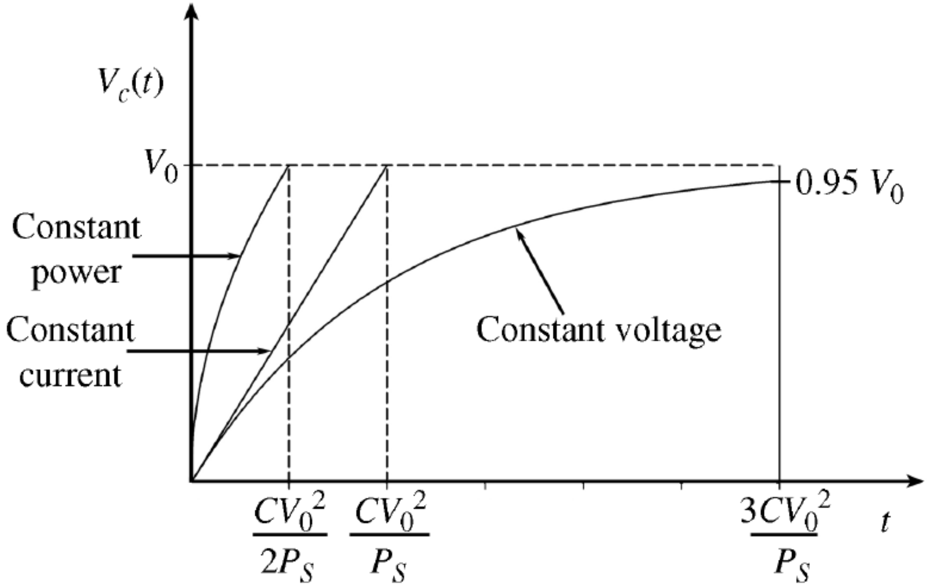
$$\Rightarrow \quad \frac{1}{2}CV_C^2(t) = P_s t$$

- The voltage on the capacitor is

$$V_C(t) = \sqrt{\frac{2P_s t}{C}}$$

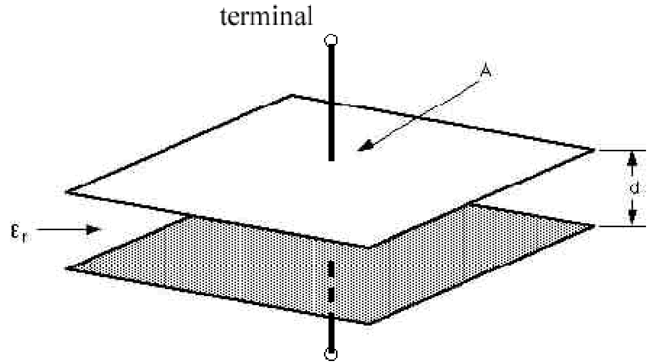
- The charging time is

$$T_{ch} = \frac{CV_0^2}{2P_s}$$



→ Two times faster than constant current charging

Energy storage capacitor



$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$

A = surface area of parallel plate
d = separation of plates

- High-voltage capacitor

High energy cap (0.3 kJ/kg)

Self healing cap
for laser market

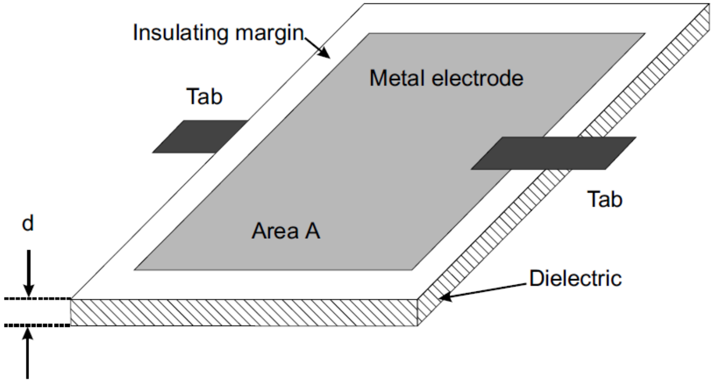
- Supercapacitor (ultracapacitor)

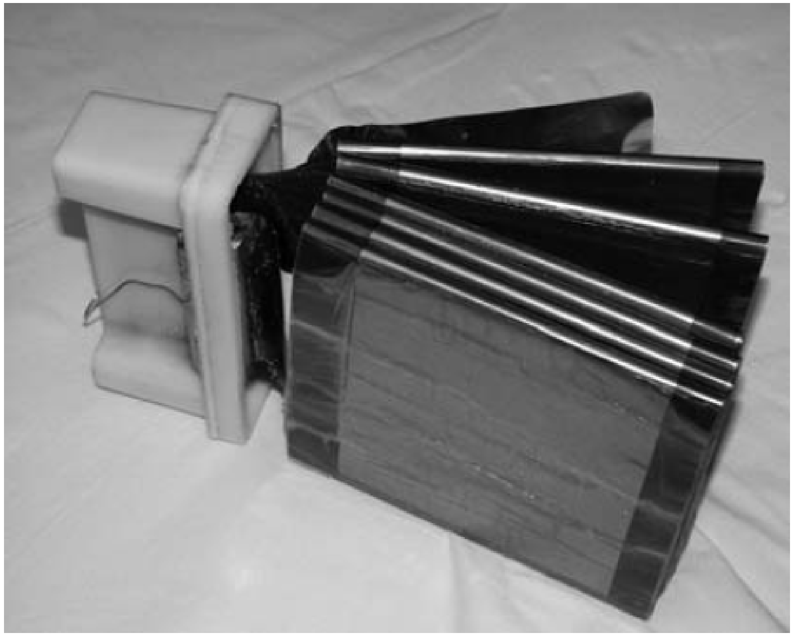
Super caps:

2.3 V, 100 F,
125 A peak current
Size: 35 x 60 x 20 mm
Weight: 35 g
ESR: 15 mOhm
Energy/weight: 7.5 kJ/kg

(Peak electrical output comparable to a Li-Ion battery with ten times the weight.)

Inside a high-voltage capacitor

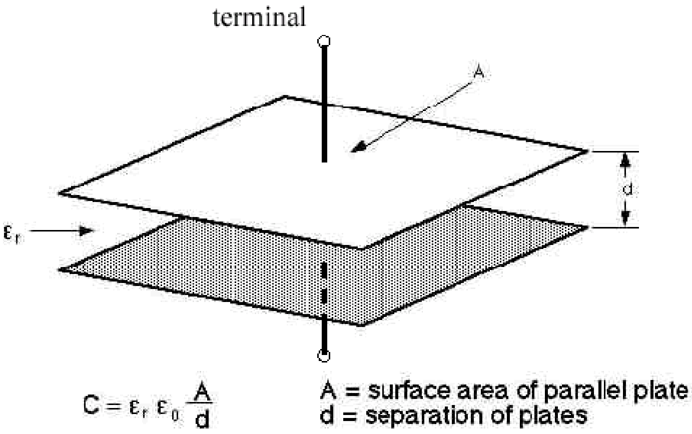


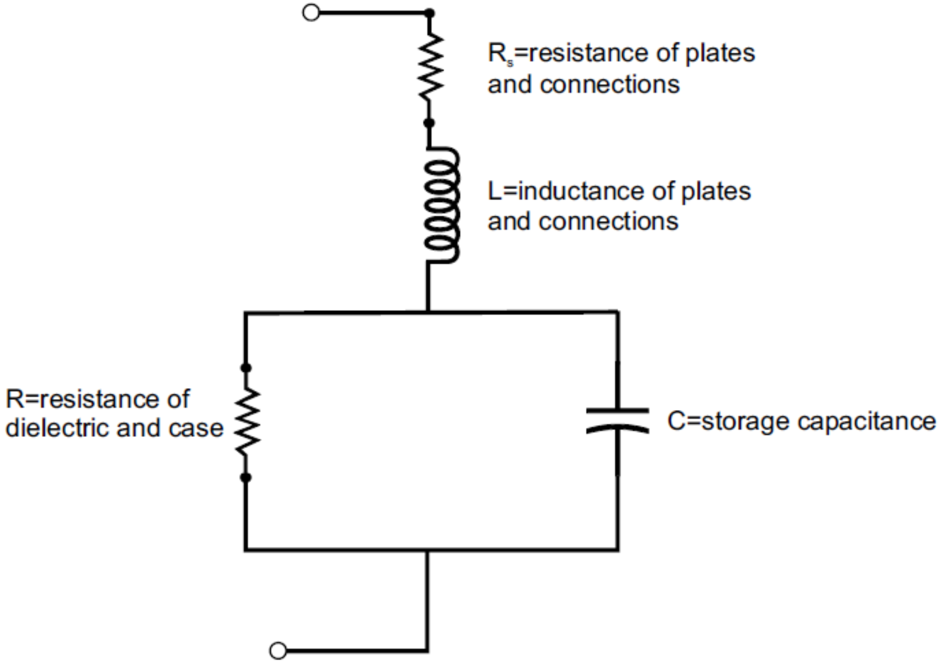


- Dielectric materials

Material	ε	E_{DB} (kV/cm)	tg(δ)
Impregnated paper	3–4	200–800	0.01–0.03
Epoxy	3.5	320	0.014
Mylar	3	400	0.001
Polypropylene	2.55	256	0.0005
Teflon	2.1	216	0.0002
Kapton	3.4	2800 (25 µm)	0.01
Plexiglas	3.3	200	0.009
Transformer oil	3.4	400	0.0002
Aluminiumoxide	8.8	126	0.01
Bariumtitanate	1143	30	0.01
Glass (borosilicate)	4.84	157	0.0036

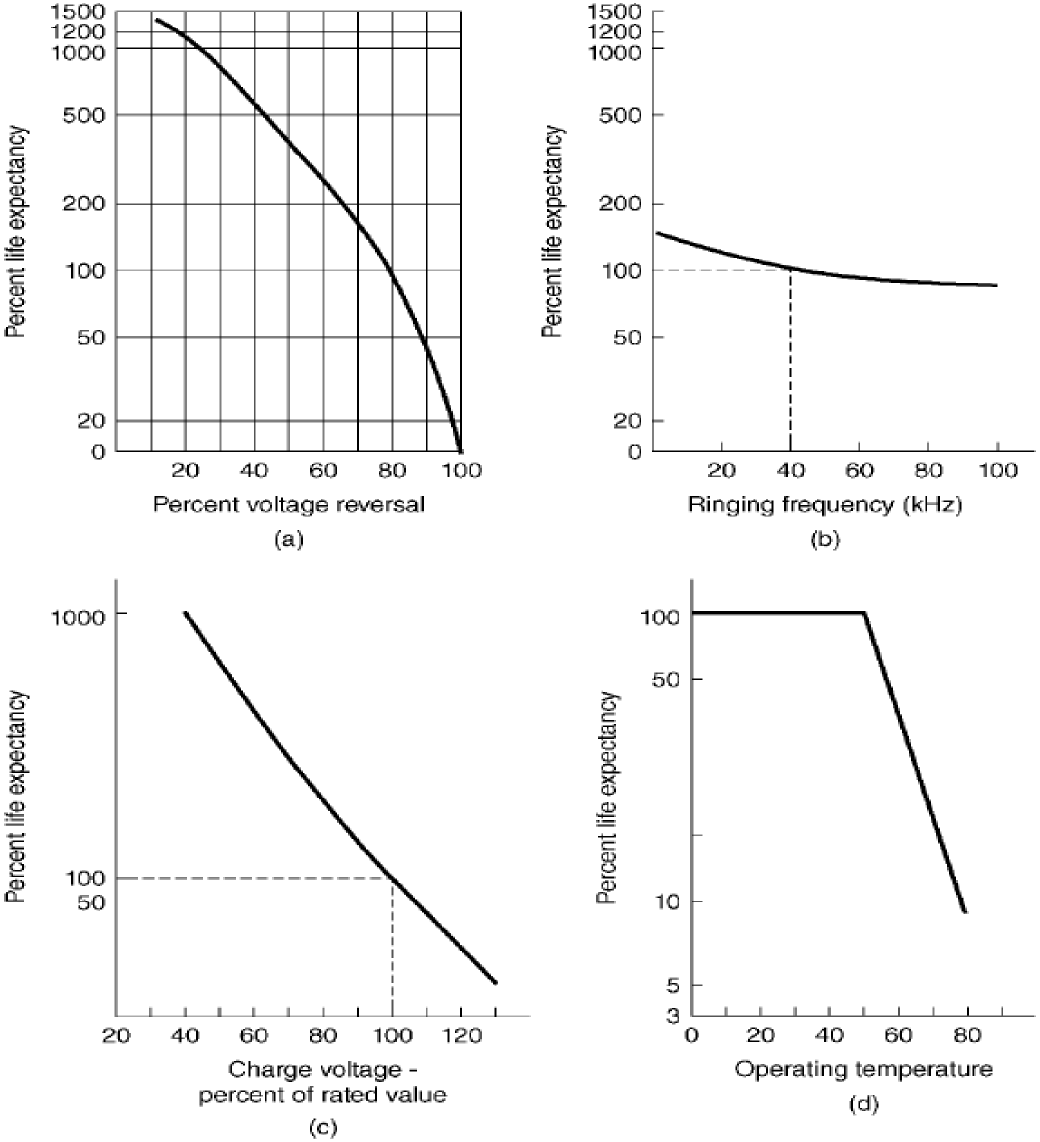
Equivalent circuit model of a capacitor



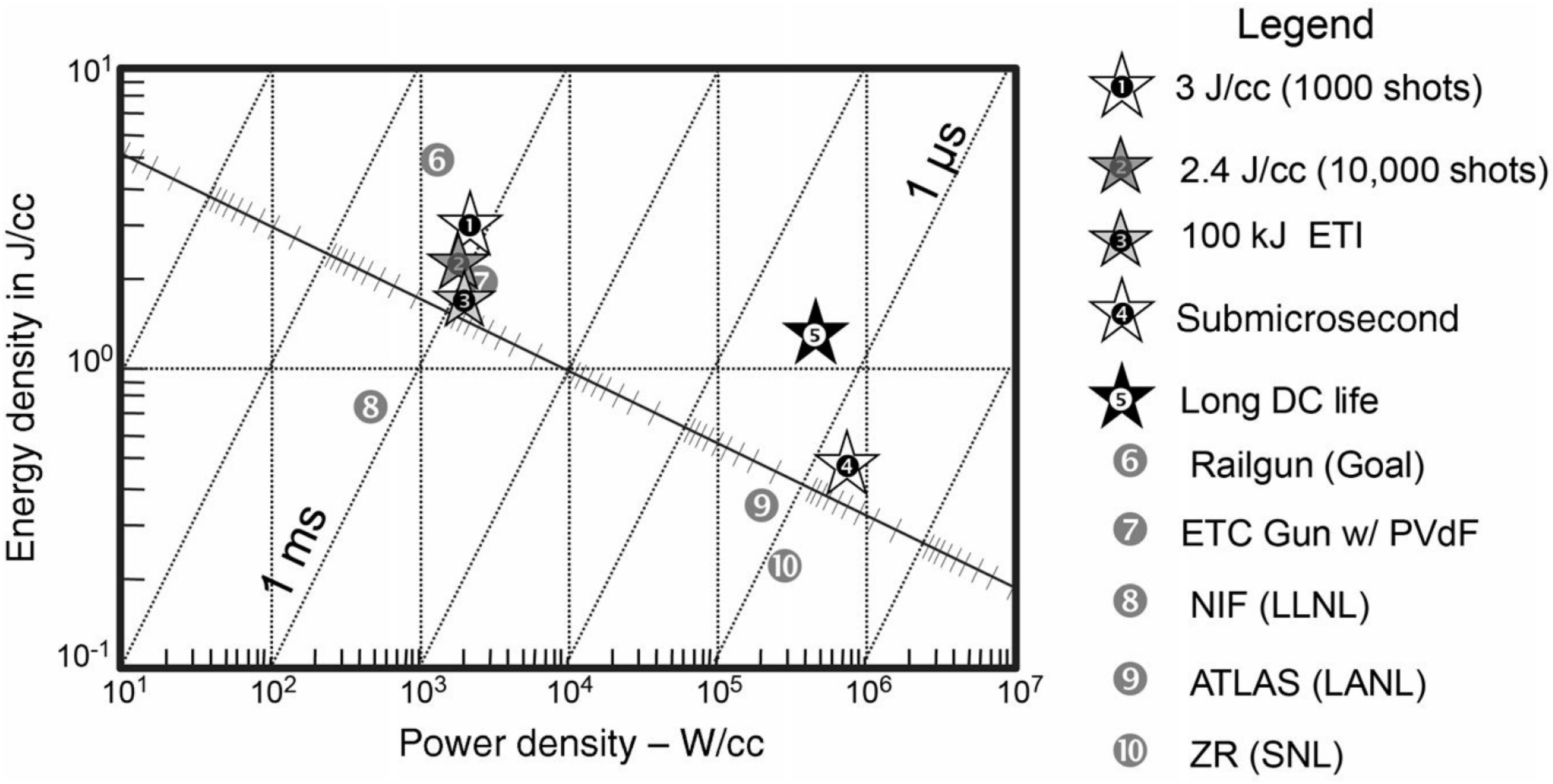


- ESR : Equivalent Series Resistance ← conductivity of electrode and connection
- ESL : Equivalent Series Inductance ← depend on the geometry of electrodes, connection, leads…

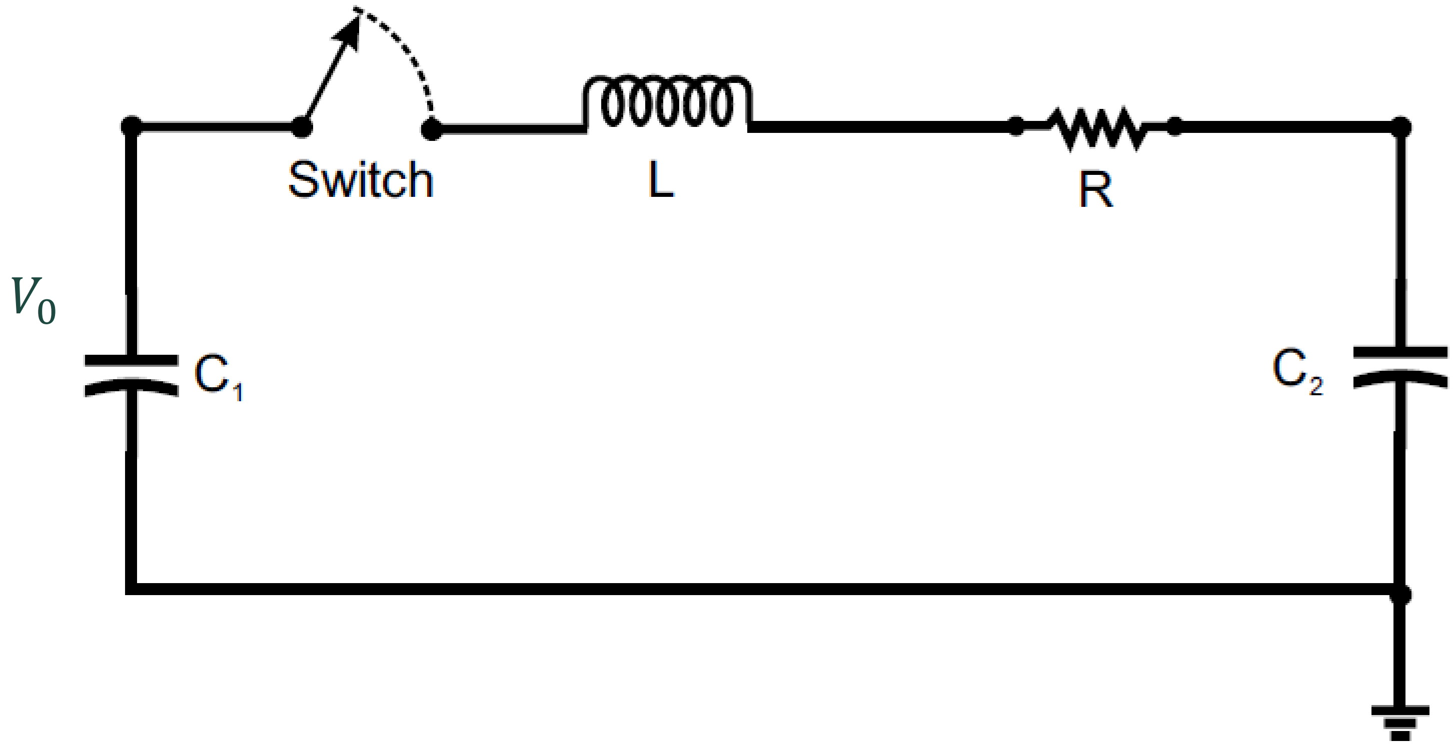
Life expectancy curves



Advances in several capacitor technologies



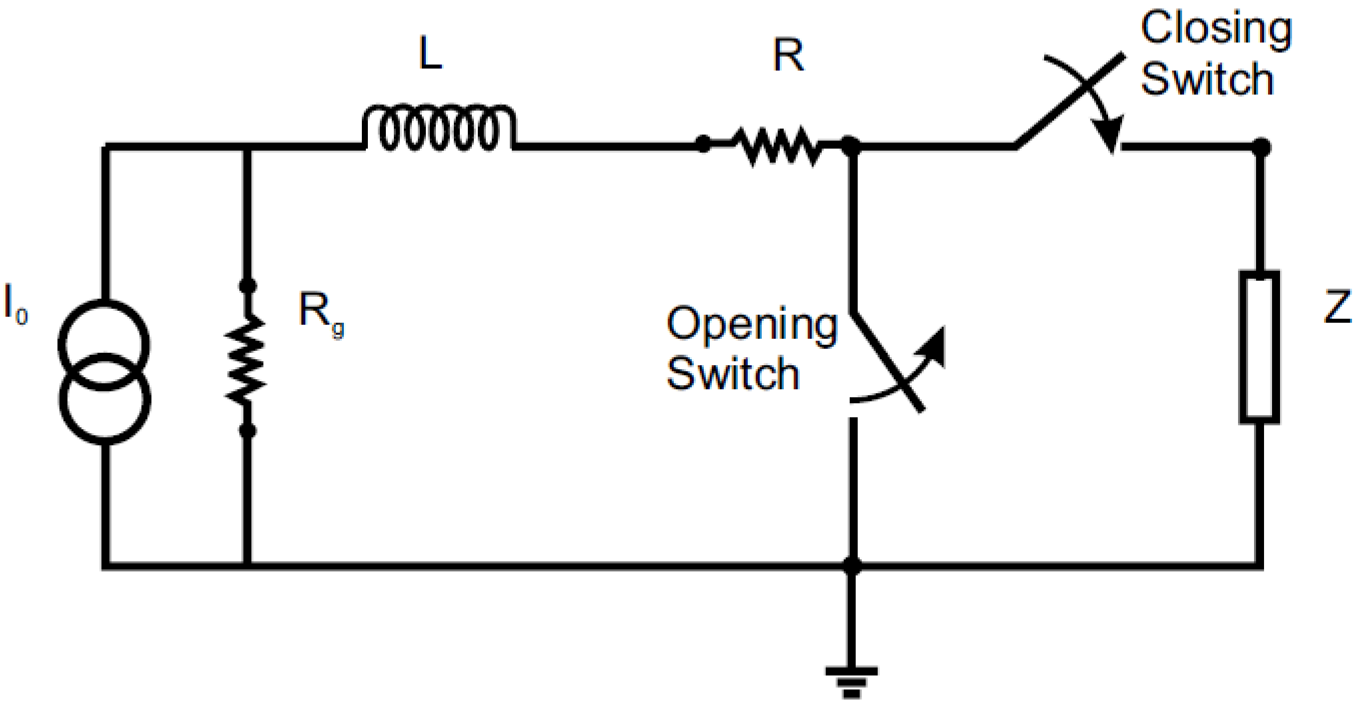
Energy transfer: CLRC circuit



Homework:

1) Solve $I(t)$ for three different regimes.
2) Find the peak current and the time for the peak current.
3) Find the voltage on C_2 and discuss the energy transfer efficiency.

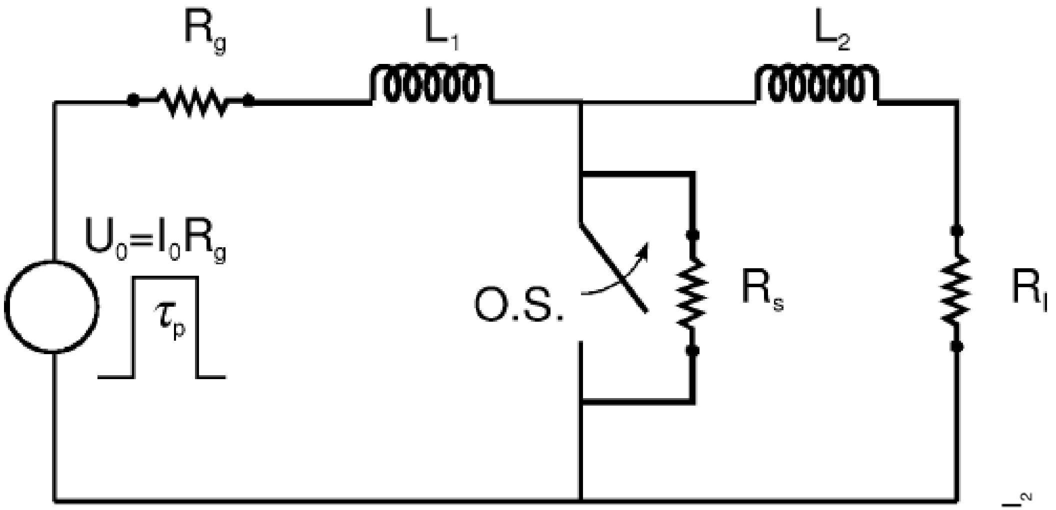
Inductive energy storage



During the inductor charging:

$$I(t) = I_0 \frac{R_g}{R + R_g} \left(1 - e^{-[(R+R_g)/L]\,t}\right)$$

Inductive energy storage: discharging



$$P_{\mathrm{m}} = \frac{R_{\mathrm{l}} L_1^2 I(0)^2}{(L_1+L_2)^2}\left(1-\frac{2}{x}(\ln x+1)\right),$$

$$x = \frac{R_{\mathrm{s}} L_1}{L_2(R_{\mathrm{g}}+R_{\mathrm{l}})} \gg 1\,.$$

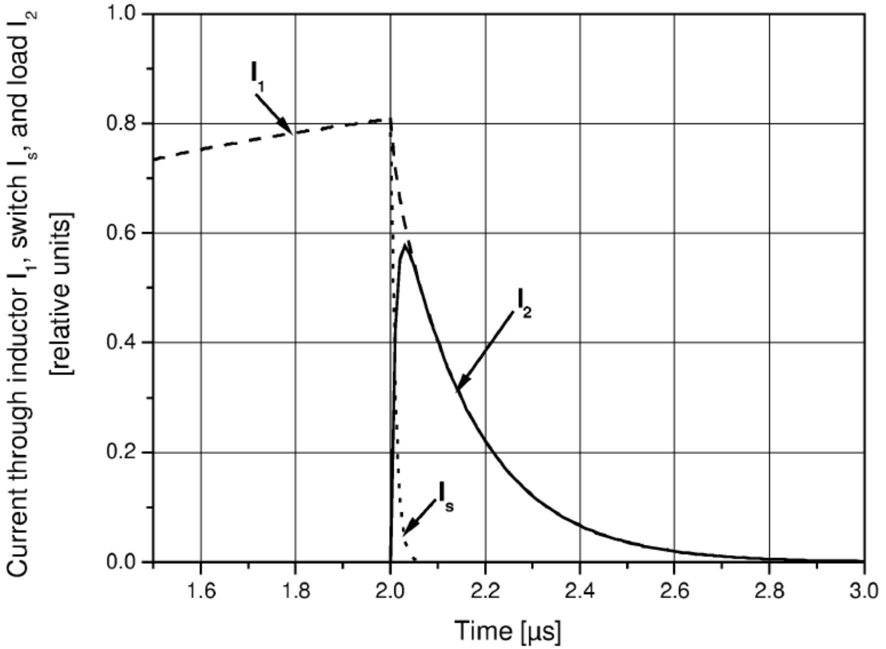
$$P_{\mathrm{al}} = \frac{I_0^2 R_{\mathrm{g}}}{4}$$

Power multiplication:

$$M = \frac{P_{\mathrm{m}}}{P_{\mathrm{al}}} \approx \frac{4R_{\mathrm{l}}}{R_{\mathrm{g}}}\,\frac{L_1^2}{(L_1+L_2)^2}\left(1-\mathrm{e}^{-R_{\mathrm{g}}\tau_{\mathrm{p}}/L_1}\right)^2$$

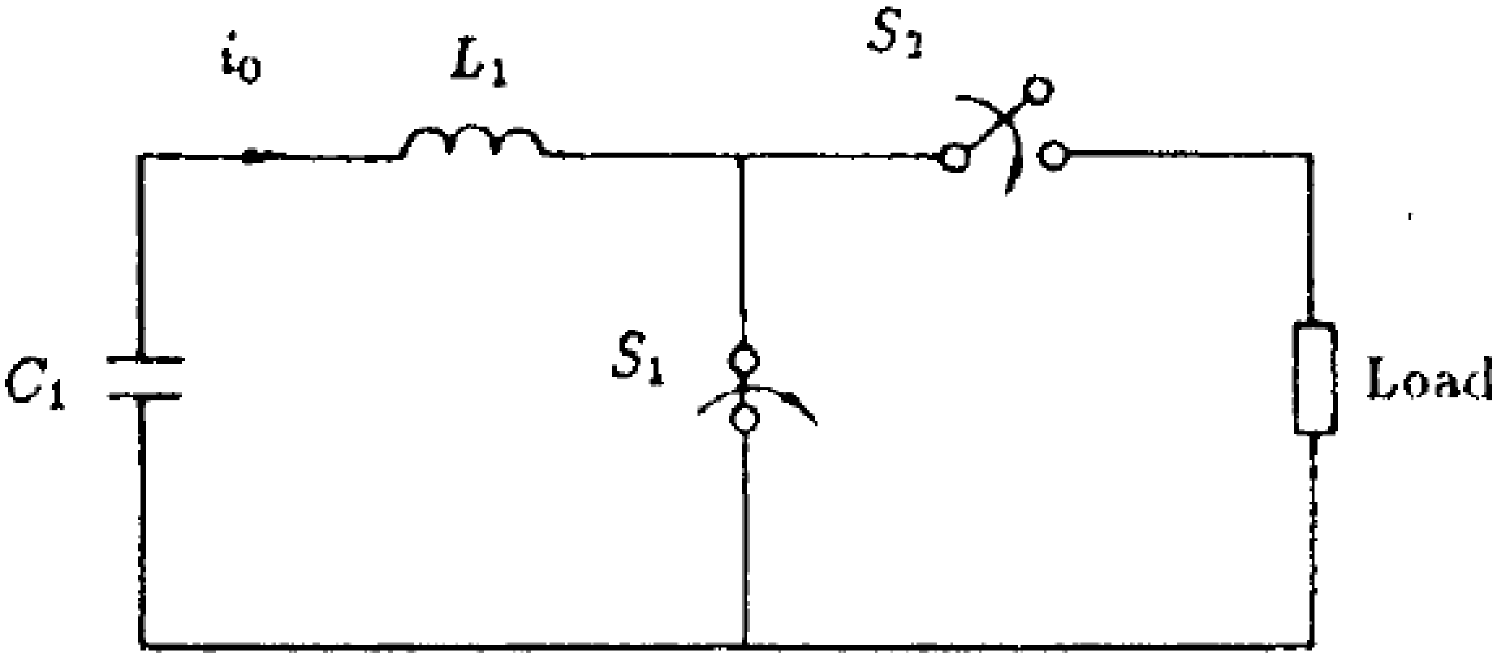
Voltage multiplication:

$$M_V \propto \frac{R_{\mathrm{l}}}{R_{\mathrm{g}}}\,\frac{L_1}{L_1+L_2}\,\frac{I(0)}{I_0}$$



Inductive circuit driven by capacitor discharge

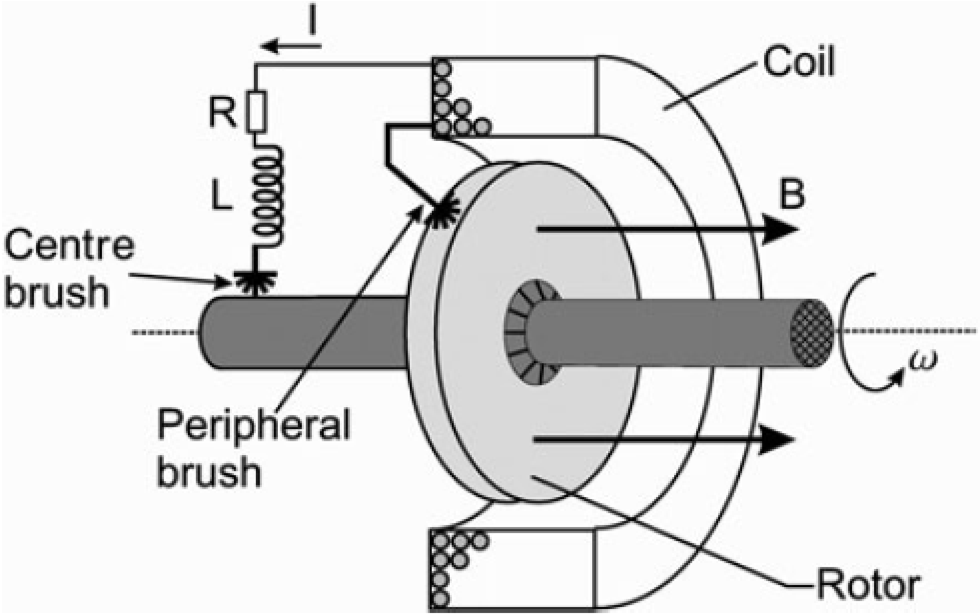
- High current is achieved by capacitive discharge.
- Voltage multiplication is achieved by opening switch.

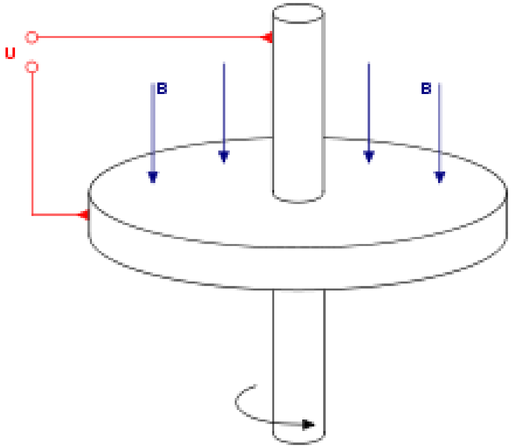


Inertial energy storage

- Homopolar generator

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



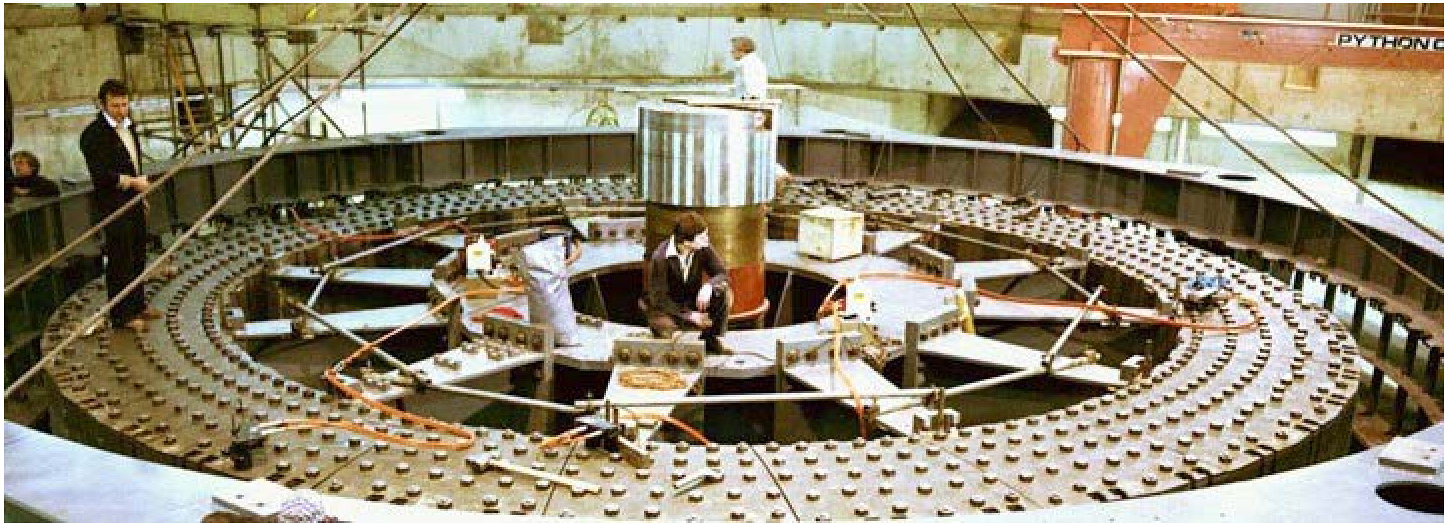


$$U = -\frac{\mathrm{d}}{\mathrm{d}t}\int \vec{B}\cdot\mathrm{d}\vec{A} = -\int \frac{\partial}{\partial t}\vec{B}\cdot\mathrm{d}\vec{A} - \oint(\vec{B}\times\vec{u})\cdot\mathrm{d}\vec{s}$$

$$\frac{1}{2}\Theta\omega^2 + \frac{1}{2}LI^2 + \int_0^t I^2R\,\mathrm{d}t = \frac{1}{2}\Theta\omega_0^2$$

Inertial energy storage

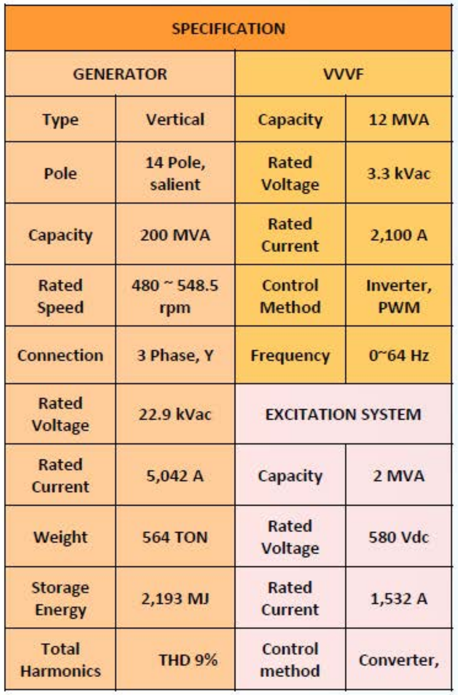
- Motor-generator system for JET



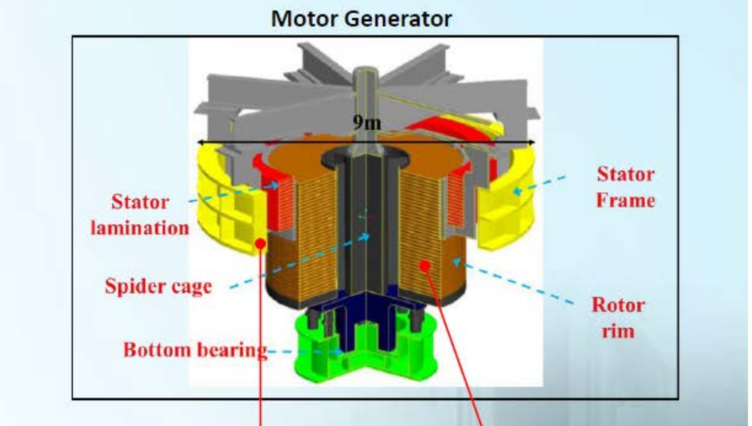
- Two flywheels
- Stored energy: 2.6 GJ each
- Peak power: 400 MW each
- Duration: 50 ~ 300 sec

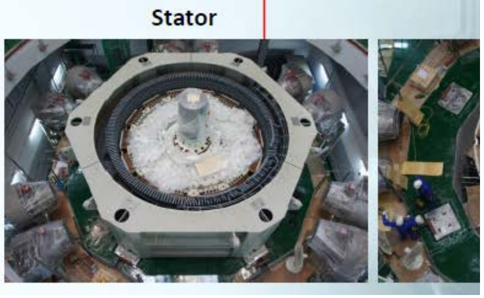
Inertial energy storage

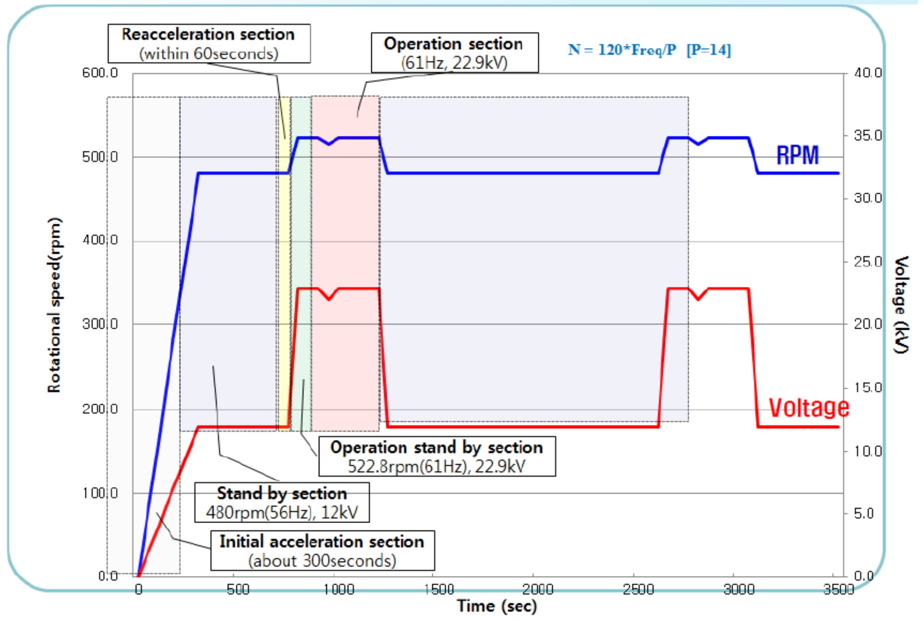
- Motor-generator system for KSATR



SPECIFICATION			
GENERATOR		VVVF	
Type	Vertical	Capacity	12 MVA
Pole	14 Pole, salient	Rated Voltage	3.3 kVac
Capacity	200 MVA	Rated Current	2,100 A
Rated Speed	480 ~ 548.5 rpm	Control Method	Inverter, PWM
Connection	3 Phase, Y	Frequency	0~64 Hz
Rated Voltage	22.9 kVac	EXCITATION SYSTEM	
Rated Current	5,042 A	Capacity	2 MVA
Weight	564 TON	Rated Voltage	580 Vdc
Storage Energy	2,193 MJ	Rated Current	1,532 A
Total Harmonics	THD 9%	Control method	Converter,



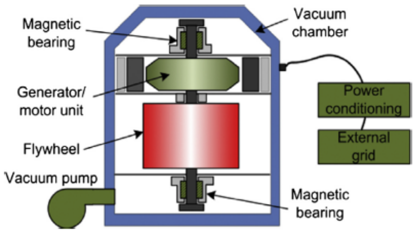




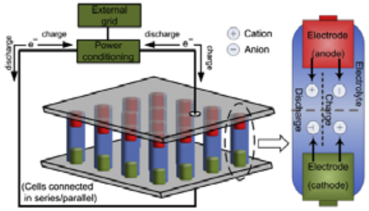
Electrical energy storage (EES) for power grid

X. Luo et al., Applied Energy 137, 511 (2015)

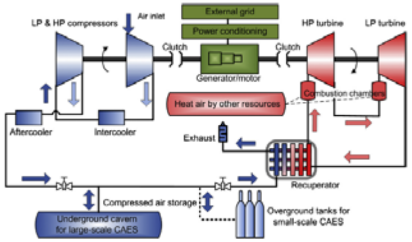
FES (flywheel energy storage)

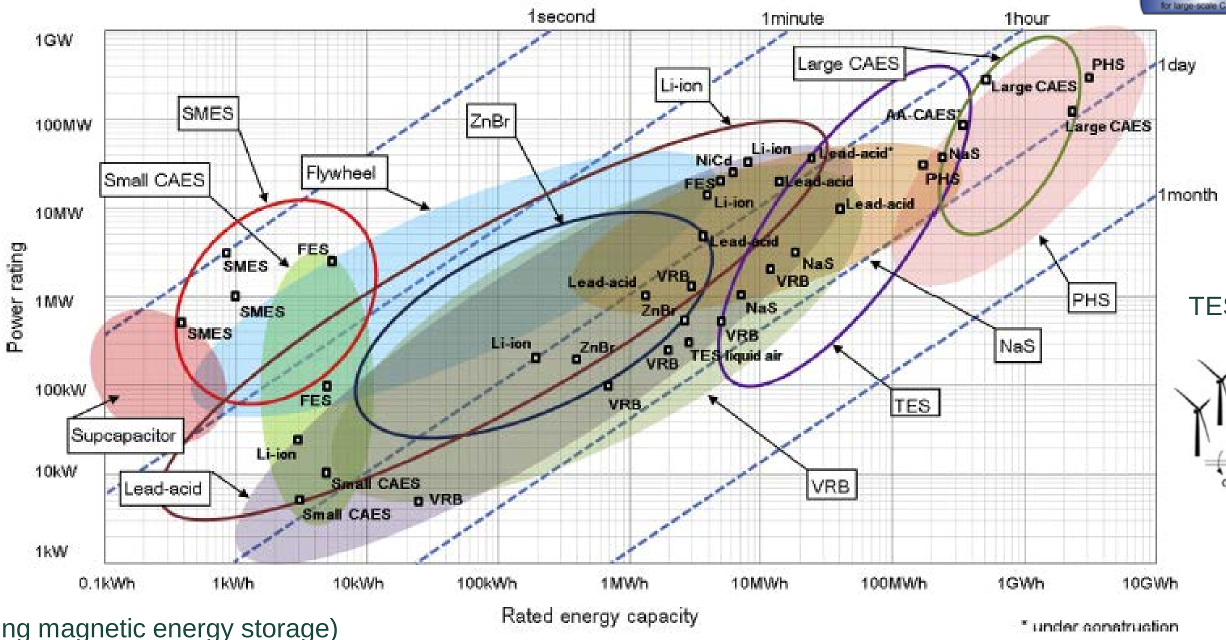


BES (battery energy storage)

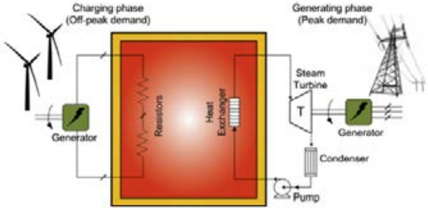


CAES (compressed air energy storage)

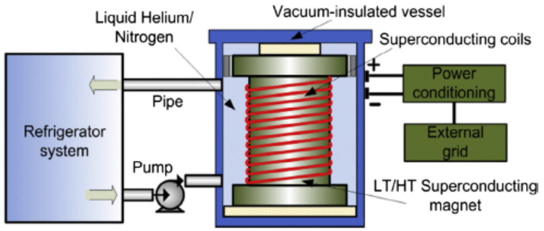


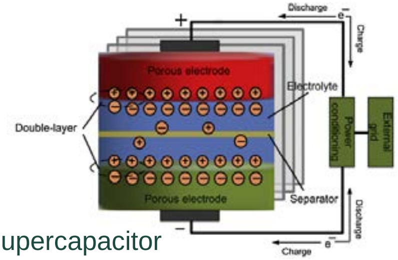


TES (thermal energy storage)



SMES (superconducting magnetic energy storage)





Supercapacitor

PHS (pumped hydroelectric storage)