Introduction to Pulsed Power

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Introduction

- Pulsed power technology is an area of interest to physicists and engineers in fields requiring high voltages and large currents.

- Modern pulsed power runs the gamut from its historical roots in flash radiography, X-ray generation, and the simulation of weapons effects, such as nuclear electromagnetic pulse (EMP), to packaged pulsed power for directed energy weapons and biological and medical applications. New applications and techniques continue to emerge.

References

Plasma: energy compression in space

- Generation of spatial region where energy state is higher than surroundings (tokamak, processing chamber, plasma jet)
  - Generation of energetic particles, chemically active species
- Energy confinement (compression) in space
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: $E = 1 \text{ kW} \times 1 \text{ sec} = 1 \text{ kJ}$
  $P = 1 \text{ kJ} / 1 \text{ us} = 1 \text{ GW}$
Features of pulsed power

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

**High Power (大電力)**

- Short rise time
- Short pulse width
- Focusing of high power in a narrow space

- Generation of high voltage and current
- New application of electromagnetic energy
Features of pulsed power

- Pulsed power is a special power conditioning technique that transforms the characteristics of the prime energy source to the electrical requirements of the load.

- Energy from a primary source is accumulated over a relatively long time scale and compressed into pulses of high instantaneous power.

- Several stages may be needed to fully exploit the time dependence of breakdown of insulating materials to deliver energy with the required time dependence and amplitude for the application.

- The resulting peak power delivered to the load has a large ratio of instantaneous-to-average power.

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<table>
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<tbody>
<tr>
<td>Energy per pulse</td>
<td>$1 \times 10^7$ J</td>
</tr>
<tr>
<td>Peak power</td>
<td>$10^6 \times 10^{14}$ W</td>
</tr>
<tr>
<td>Peak voltage</td>
<td>$10^3 \times 10^7$ V</td>
</tr>
<tr>
<td>Peak current</td>
<td>$10^3 \times 10^8$ A</td>
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<tr>
<td>Pulse width</td>
<td>$10^{-10} \times 10^{-5}$ s</td>
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Pulse shape parameters
Typical waveform of repetitive pulses

\[ D(\text{duty}) = \frac{T_{on}}{T_{on} + T_{off}} \]
RF pulse
Generation of high power pulses
Typical pulsed power systems

- **Capacitive**

  Capacitive storage: \( w_c = \varepsilon_0 E^2/2 \) (10-80 kJ/m\(^2\))

- **Inductive**

  Inductive storage: \( w_i = B^2/(2\mu_0) \) (1-50 MJ/m\(^2\))
Applications of pulsed power

- High Energy Density Plasma
  - Nuclear fusion plasma, X-ray generation, Pinch plasma

- High Power Pulse Laser
  - Solid state laser (Nd:YAG), Gas laser (Excimer, CO2, Nitrogen)

- Particle Beam Generation & Application
  - Electron (Ion) acceleration, Material processing, Surface treatment

- Electromagnetic Acceleration
  - Rail gun (EM gun), Electrothermal chemical gun (ETC gun), Electromagnetic Forming

- Electromagnetic Wave Generation
  - High power microwave (HPM), Electromagnetic pulse (EMP)
Applications of pulsed power

- Industrial applications
  - Metal shaping (complex geometries)
  - Nano-sized particle fabrication
  - Rock blasting (at construction site)
  - Exhaust gas treatment
  - Thermal power plant (electric dust collector)
  - Waste water treatment (organic matter decomposition)
  - Ballast water treatment
Examples of pulsed power

- Lightning vs Pikachu
Examples of pulsed power

- High energy density plasmas (HEDP)

Z-pincho plasma

Plasma focus

MIF

Plasma thruster

Spheromak formation

Pulsed IEC
Examples of pulsed power

- Z machine (SNL) : X-ray generator

- The Z Pulsed Power Facility, informally known as the Z machine, is the largest high frequency electromagnetic wave generator in the world and is designed to test materials in conditions of extreme temperature and pressure. Since its refurbishment in October 1996, it has been used primarily as an inertial confinement fusion (ICF) research facility.
Examples of pulsed power

- WDM (Warm dense matter) or HEDP research

**Warm dense matter research using wire explosion**

**Intense X-ray generation by pulsed X-pinch**

- Electrical conductivity and wire temperature measurements

- 

\[ \sigma = \sigma(\rho, T) \]
Examples of pulsed power

- Pulsed ion beam → pulsed D-D beam-target fusion neutron source

Pulsed D-D neutron source
(10^4 neutrons / 10 us)

- 8x10^4 n/pulse
- 150 keV, 500 mA pulsed D^+ beam
- Process for metal-hydride reservoir & target

Compact, sealed-type D-D neutron generator

- Sealed-off
- D_2 gas reservoir (Zr powder)
- TiD_2 target

Ion source
Examples of pulsed power

- Beam-plasma target fusion proton source
- If we increase the electron temperature of target plasma by mirror-confinement, the slowing down time of the injected particle is greatly increased, increasing beam-target interaction probability.
- Neutron production is possible if D₂ gas is used as a target. → BNCT
Examples of pulsed power

- Fusion (MCF vs. ICF)
Examples of pulsed power

- VEST
Examples of pulsed power

- Laser fusion

NIF aims to create a single 500 terawatt (TW) flash of light that reaches the target from numerous directions at the same time, within a few picoseconds. The design uses 192 individual "beamlets", which are amplified in 48 beamlines containing 16 laser amplifiers per line, each one amplifying four of the beamlets.
Examples of pulsed power

- Railgun

**Railguns Magnetic Field Effect**

- Driving Current
- Armature Current ($i$)
- Armature Magnetic Field
- Negative Conducting Rail ($L$)
- Magnetic Field ($B$)
- Positive Conducting Rail ($I$)
- Armature
- Projectile

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Examples of pulsed power

- **Coilgun**

A coilgun is a type of projectile accelerator that consists of one or more coils used as electromagnets in the configuration of a synchronous linear motor which accelerate a magnetic projectile to high velocity.
Examples of pulsed power

- ETC (Electro-thermal Chemical) gun
Examples of pulsed power

- High Power Microwave or EMP
Examples of pulsed power

- EM forming
Examples of pulsed power

- EM blasting

0.03 m³ concrete block
Examples of pulsed power

- **Underwater shockwave generation**

  - Electric current
  - Shock wave
  - Spark
  - Well screen

  ![Image of underwater shockwave generation setup]

  **Examples of underwater shockwave generation**
  - Underwater shockwave generation
  - Slurry treatment
  - Groundwater purification
  - Redox removal
  - Soil strengthening
  - Rock blasting

  ![Images of underwater shockwave generation application]

  **Technical commercialization**
  - Water high-frequency wave generation
  - Sludge treatment
  - Groundwater purification
  - Redox elimination
  - Soil strengthening
  - Rock fragmentation

  **References**
  
  정경재 외, 대한지질공학회지 23, 29 (2013)
  K. Lee et al., J. Appl. Phys. 121, 243302 (2017)
Examples of pulsed power

- Water-bloom removal

  ![Water-bloom removal](image)

  → Shock wave destroys gas vesicles to sink the water-bloom down to the bottom

- NOx removal

  ![NOx removal](image)

  40 kV, 4 MW, 0.15 J/pulse, 100 Hz
  → 20% reduction of NOx with 15 W