EMP Resilience for the Grid of the Future

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X-rays & \( \Gamma \)-rays
High Altitude Electromagnetic Pulse (HEMP)

\( \gamma = \text{gammas} \)
\( e_\gamma = \text{Compton electrons} \)
\( B_{\text{Geo}} = \text{geomagnetic field} \)
\( E = \text{electric field} \)
\( H = \text{magnetic field} \)
\( P = \text{Poynting vector} \)
EMP a rising concern throughout the 1950s

Enrico Fermi was concerned
About EMP at Trinity test

Peter Haas identified EMP’s tactical importance during The PLUMBOB test series.
Partridge at Los Alamos was developing fast sensors to measure the newly discovered EMP. Partridge archives progress in the new Sensor and Simulation Note Series.

Baum was identifying issues in taking measurements in the presence of ionizing radiation.

After 1962, a simulation capability was required for testing.
EMP is a double exponential waveform similar to lightning.

The risetime for EMP simulators is nanoseconds where lightening simulators are microseconds.
Systems are complicated by items to test

Sea Trials for EMP measuring sytem (Lt. Baum gets his sea legs)
Nuclear Simulations Begin at Sandia

In a quest to make very energetic x-rays, Sandia hears about Martin’s group at AWE at a technical interchange (JOWOG) meeting.
Lasting Contribution by the EMP community

Capacitive (D-dot) probe
By Partridge (1964) (SSN 4)

Fast Sensor Development

Documentation and Archiving
Entire Note Series available from Summa Foundation

ece-research.unm.edu/summa/
Time and Frequency Characteristics of HEMP

- Early-Time \( E_1 \)
  - Prompt Gamma Signal
  - Scattered Gamma Signal
  - Neutron Inelastic Scattering
  - Geomagnetic Disturbances

- Intermediate-Time \( E_2 \)

- Late-Time \( E_3 \)

- Spectral Density (\( [\text{W/m}^2] / \text{Hz} \))
  - \( \sim 10^{-3} \)
  - \( \sim 10^{-4} \)
  - \( 1/\omega \)
  - \( 1/\omega^2 \)

- Frequency [Hz]
  - \( \sim 10 \text{ kHz} \)
  - \( \sim 1 \text{ MHz} \)
  - \( \sim 10 \text{ MHz} \)
  - \( \sim 300 \text{ MHz} \)
  - \( \sim 1-10 \text{ GHz} \)

- EMI Environments
- Lightning
- HEMP
- Wideband (UWB)
- Narrowband

Range dependent (e.g., HPM, HRF, etc.)
Is the Smart Grid Susceptible to HEMP?

EM Coupling is Frequency Dependent

Figure 2-34. Magnetic leakage through an aperture.
EMP Commission: ... In the event of a major EMP attack on the Grid, 8 out of 10 Americans could be dead within a year ....”
Standards

10/350 μs characterizes direct lightning strike

8/20 μs for surge testing IE 61643-11

1.2/50 μs for overvoltage caused by lightning strikes

HEMP 1/23 ns! 0.001/0.023 μs
Lightning Surge Arrestor Types

In general, lightning surge arrestors will not protect against EMP.
Atmospheric Air: Time Dependent Breakdown

\[ F = 168.8 \cdot p^{0.7} t_{\text{eff}}^{-0.25} \]

Spark gap based protection for surge & lightning will not work for EMP
External Gap Lightning Arrestors

Photo taken near San Luis, CO

Photo courtesy of F. Mark Lehr

www.arresterworks.com
Metal Oxide Varistor Lightning Surge Arrestors

ZnO is most common material but all varistors are mixtures of metal oxide with filler.
A lightning arrester is essentially a collection of billions of microscopic junctions of Metal Oxide Grains that turn on and off in microseconds to form a current path from the top terminal to the ground terminal of the arrester.
Our Task: Equivalent Circuit Model

MOV Stacks

cartridge

BigCliveDotCom  https://www.youtube.com/watch?v=7hvg2Wey92E
Equivalent Circuit Models for LSAs

Fig. 1. IEEE Frequency-dependent model

Fig. 3. PINCETI model

Fig. 4. P-K model
Frequency content

\[ t_{mr} = \frac{V_{\text{peak}}}{\dot{V}} \] \quad \text{More precise measure of maximum derivative than 10-90 risetime}

Peak rate of voltage rise: \( t_{mr} \)

\[ f_{\text{max}} = \frac{1}{t_{mr}} \sim 1 \text{ GHz} \]

\( \lambda \sim 30 \text{ cm} \sim 1 \text{ foot} \)

\[ 0.1 \lambda < d_c < 10 \lambda \quad \rightarrow \quad \text{Distributed Element} \]
LSA is a Distributed Element for EMP!

Distributed Element: where the phase of the voltage or current changes significantly over the physical extent of the device because the device dimensions are on the order of the electrical wavelength

All Lightning Surge arrestors must be treated as microwave circuit elements for EMP!
Zeroth Order Equivalent Circuit model
Next Up: Material Response of Varistors

ZnO

Self Matching Pulser
10 ns risetime
100 ns pulsewidth
1-40 kV

miniMarx: < 1 ns risetime
200 kV
Peaking Circuit for EMP Simulation

850nm, 100W Laser Diodes

GaAs PCSS
Photoconductive Solid State Switches
75 kV / 1.5 kA with an 800 ps risetime
Promising EMP Protection Devices

Cross Sectional Diagram

- Ti/Au Bond Pad
- Optical Trigger
- Contact Metal
- Current Filament
- Bottom Contact

Vertical GaN High Gain PCSS

(New)
Fast Response Varistor