# Zones of Vulnerability

**Frank Rahn, Chief Scientist**
**Whitney Research Services**

**Resilient Smart Grid Customers**
Brookhaven National Laboratory
April 3-4, 2014

- **Critical Customers**
  - Identification of Critical Customers
  - What to protect
  - How to protect
  - Interfacing Infrastructure

- **Silent Threats**
  - Unknown unknowns
  - The 3 Ninjas (Maintenance, Vegetation, Indifference/Inertia)
  - Deliberate attack
  - Co-location, Common Cause

- **Response**
  - Ride-thru issues
  - Coping times
  - Reconfiguration
  - Emergency Procedures / Training

- **Communication Issues**
  Before, during and after, especially priorities

- "The outcome of the battle has been already decided before the first arrow is loosed"

  Sun Tzu

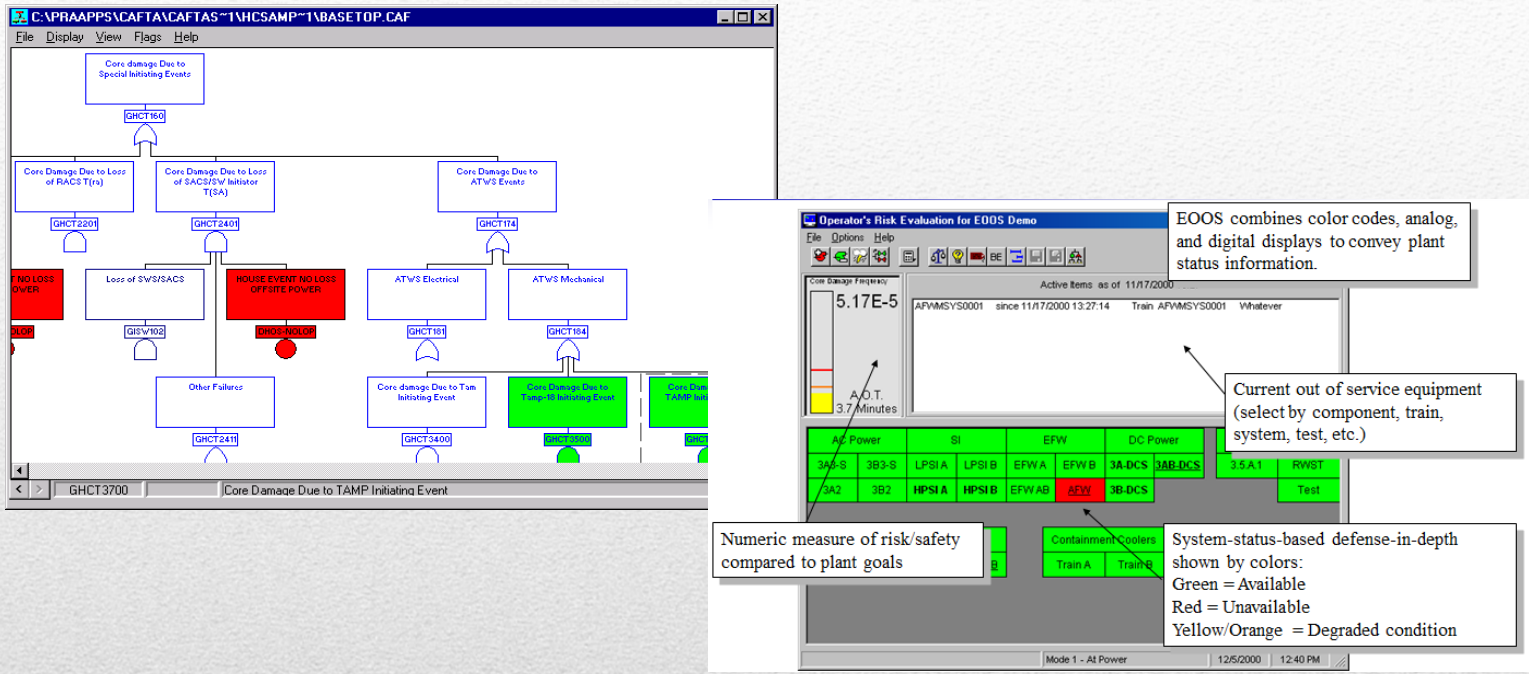
- “He who protects everything, protects nothing”

  Frederick the Great (and others)

- “Be Prepared”

  Boy Scout Motto

- Proper design, preparation and prior response planning will dominate the unrolling of events
- Risk must be prioritized to forestall unacceptable consequences
- Risk must be considered for multiple failures
  - N-1 vs N-1-1 vs N-2 considerations
  - Analysis is guide to our thinking
- Other industries have lots to contribute

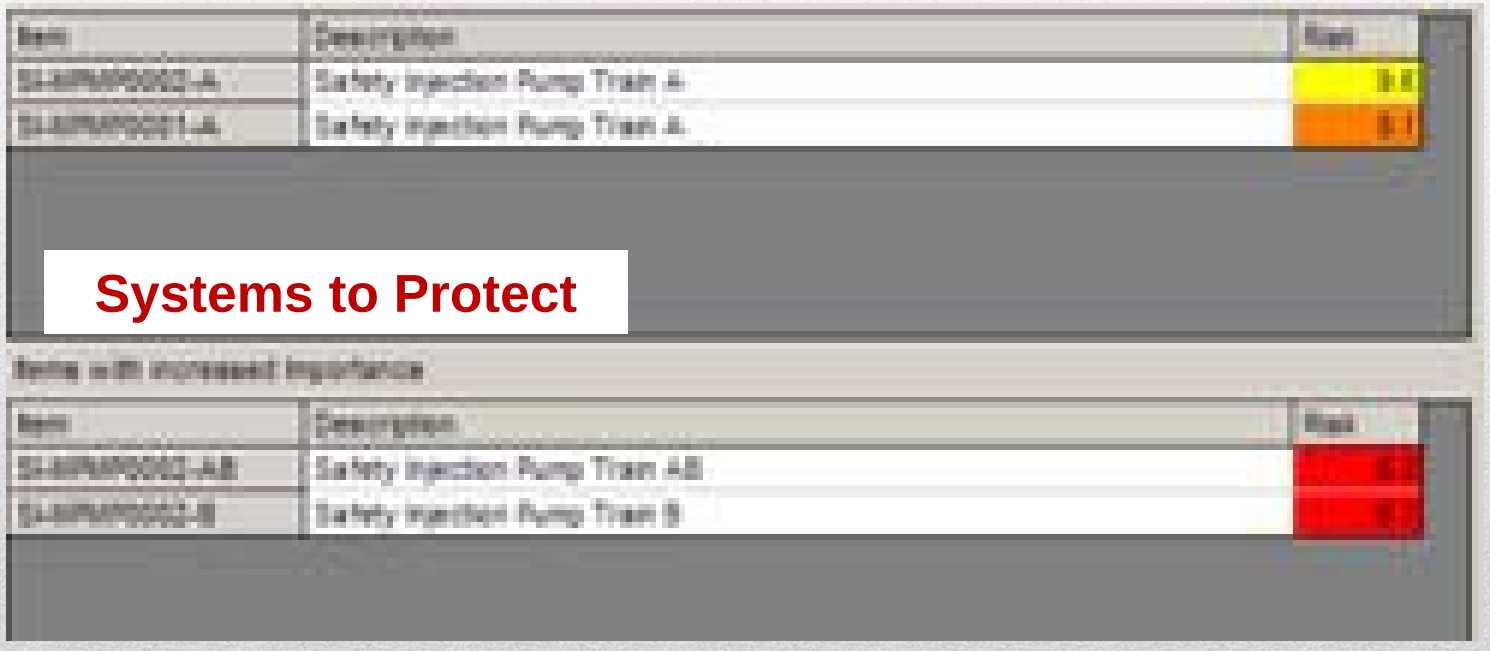



| | |
|---|---|
| **CAFTA - Fault Tree Analysis** | **Multiple Failure Vulnerabilities** |
| **SETS - Success Paths** | **Failure Prevention under Degraded Conditions** |
| **EOOS – Dynamic Accident Analysis** | ***Real Time* Risk Margins & Return to Service Priorities** |

# PRA - Success Paths, Failure Paths

# Recovery from Off-normal Conditions

**Return to Service Priority**

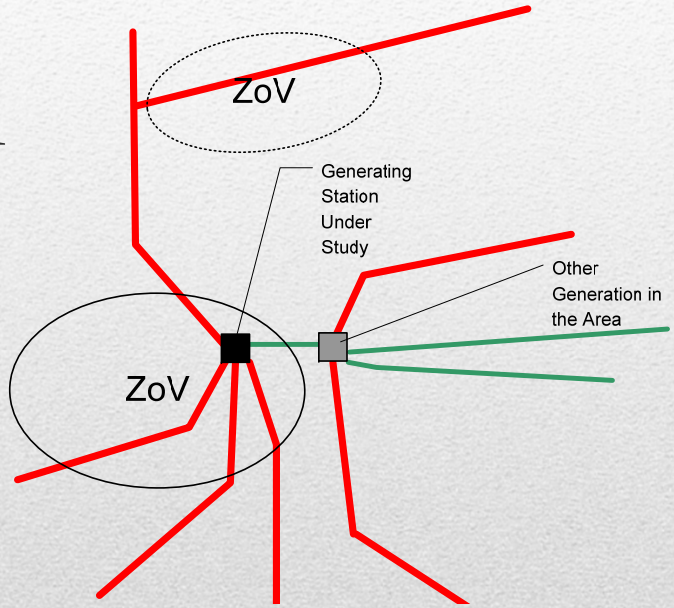



**Systems to Protect**

**Real Time Operator Guidance**

# Zones of Vulnerability

- electrical area inside which critical infrastructure would be vulnerable to events on the surrounding grid
- permits planners to determine the electrical distances where system transients are of concern




# Zone of Vulnerability (ZoV)

- Degraded power conditions leading to failures of vital equipment or extended power outages
  - undervoltage fluctuation
  - voltage spikes
  - current imbalance
- Other technical issues :
  - Load rejections and loss of load
  - Grid transients involving degraded voltage / frequency
  - Potentially damaging stress on the turbine-generator shaft
  - Complete loss of offsite power to the vital generators, e.g. nuclear plants
  - Generator trips resulting in cascading grid collapse

# Zones of Vulnerability

REDACTED

Critical Site

| Lines |
| --- |
| 500 kV |
| 345 kV |
| 230 kV |
| 10-22 kV |

# One Line Diagram of System Studied

- REDACTED

# Delimitation of the Basic ZoV

REDACTED

# Dynamic Study ZOV

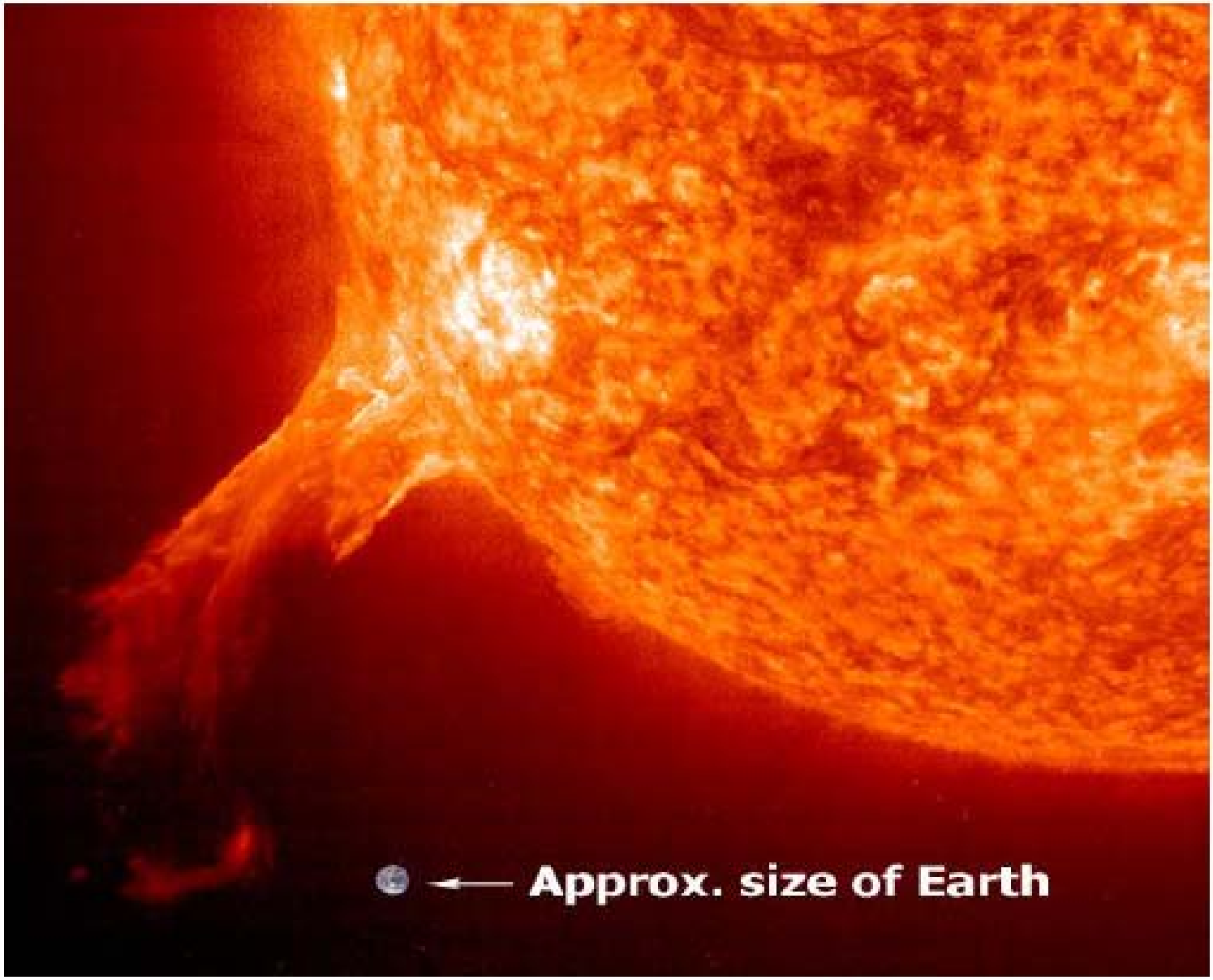
# Recommended Approach to ZOV

- **Conduct a Hazard Review:**
  - environmental threats
  - anticipated lightning surges
  - symmetric and asymmetric faults
  - switching faults, generator excitation system malfunctions
- ***Consider single failed or delayed protective device operation***
- **Review potential voltage degradations, rates and duration**
  - impact on voltage sensitive devices such as local power supplies
- ***Assess all grid faults and single failures e.g. stuck breaker, protection system, voltage regulator (N-1-1 analysis, better N-2)***
- ***Assess the voltage and frequency transients frequency limits***
  - Class 1E electrical equipment protected
  - recovery procedures are in place for emergency conditions

# Zones of Non-Vulnerability

# Moss Landing, CA

# Geomagnetic Disturbances
# aka
# Coronal Mass Discharge




A close-up of an erupting prominence with Earth inserted approximate scale of image Taken on July 1, 2002 Credit SOHO, ESA & NASA

# Geomagnetic Disturbances

- The bulk electric power system is highly complex
  - over 200,000 miles of transmission lines
- Disturbances can cause geo-magnetically induced currents (GICs)
  - can saturate high voltage transformers
- Grid more vulnerable than a few decades ago
  - high-voltage transmission lines increased by about 10x
  - higher voltages 345-765 kV
  - transmission lines more interconnected
  - equipment operating closer to its thermal rating

# GMD Historical Incidences

1989 Hydro Québec system collapsed (in 90 seconds)

- six million people without service for nine hours
- two phases of a 500kV generator step-up (GSU) transformer bank were damaged at Salem
- two 400/275kV transformers were damaged in the UK
- over 200 significant anomalies across the continent to this single storm

2003 blackout for several tens of minutes in Sweden

- transformer heating and voltage fluctuations observed in Scotland
- transformers in the Eskom network in South Africa significantly damaged
- increased on-line dissolved gas analysis (DGA) measurements on numerous GSU transformers

# Salem - Damage March 13, 1989 Storm

credit: John Kappenman, Metatech Corporation

# Limited Manufacturing Capability for EHV-Class Transformers

- Manufacturers:
  - unable to rapidly supply the large number of replacement transformers
  - backlog of nearly 3 years for all EHV transformers (230 kV and above)
  - The earliest delivery time  early 2016
- Only one US plant manufacturing a transformer up to 345 kV.
- No US manufacturing capability for 500 kV and 765 kV transformers (largest group of At-Risk transformers in the US)

# GMD Historical Incidences

- The highest magnitude GMD of the 20th century occurred in May, 1921
  - disabled all telegraph service from the Atlantic coast to the Mississippi River and in the West
  - submarine cables needed to be brought to the surface for repairs
- The strongest recorded storm is the "Carrington event" occurred September 1859
  - extraordinary auroral displays in Hawaii, the Caribbean, and Central America

# Effects on Relays

EHV transformers in bulk power transfer system (across North America)

Plant vulnerabilities:

Older static/electromechanical relays that protect shunt capacitors and static var compensators

Capacitor banks and harmonic filter banks using microprocessor relays

Transformer differential relays (regardless of type)

# if 1921 Event happened today

- About 20 percent of 345kV transformers (214 transformers), 28 percent of 500kV transformers (137 transformers), and 32 percent of 765kV transformers (17 transformers) were likely to be damaged
  - over 350 failed or damaged HV transformers across N.A. in a few hours
- 94 generator step-up transformers in the northeast
  - not only impair transmission, but also cut-off base-load power generation
- Place an additional almost simultaneous demand of over 100,000 MVARs on the power system
- Large transformers cannot be repaired in the field and take up to 12-36 months to replace

# Location of EHV Transformers
## susceptible to Geomagnetic Disturbances

**REDACTED**

# Deliberate Attack

## Shots in the Dark

A look at the April 16 attack on PG&E's Metcalf Transmission Substation

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| **12:58 a.m., 1:07 a.m.** Attackers cut telephone cables | **1:31 a.m.** Attackers open fire on substation | **1:41 a.m.** First 911 call from power plant operator | **1:45 a.m.** Transformers all over the substation start crashing | **1:50 a.m.** Attack ends and gunmen leave | **1:51 a.m.** Police arrive but can't enter the locked substation | **3:15 a.m.** Utility electrician arrives |

# Location of EHV Transformers
## susceptible to Geomagnetic Disturbances

**REDACTED**

# Case Study

## One Line Diagram Of System

**REDACTED**

# Results

- Several single point vulnerabilities, particularly
  - Ravenswood transmission line
  - Transmission switching station
  - Main incoming substation
  - Radial distribution lines
- Staff was already aware of these vulnerabilities
- Model can be quantified, but requires failure rate data
- For first iteration, quantification of model probably not worth the effort

# Summary Of Single Point Vulnerabilities

**REDACTED**

Elevation of roadway ~4 feet

Location of vulnerability

**REDACTED**

No installed lighting protection

**REDACTED**

# Effect of a Lightning Strike

## power transformer at a 138 kV substation

Transformer separation issue

# REDACTED

# High Voltage fuse failure at a 138 kV substation

# Transformer Explosion

## due to gas build up

## Fire walls / Water sprays

- Firewalls
- Fire extinguishing systems

Limit fire propagation induced by the explosion

## Efficiency ?

Venice Plant, Illinois , USA, 2000

**Fire propagated to the whole plant:**
All 9 transformers caught fire despite fire walls and fire extinguishing systems

# Preventing Cascading Transformer Failures

# Firewalls don't always work

# Conclusions

- Proper design, preparation and prior response planning will dominate the unrolling of events
- Risk must be prioritized to forestall unacceptable consequences
- Risk must be considered for multiple failures
  - N-1 vs N-1-1 vs N-2 considerations
  - Analysis is guide to our thinking
- Other industries have lots to contribute

# Whitney Research Services