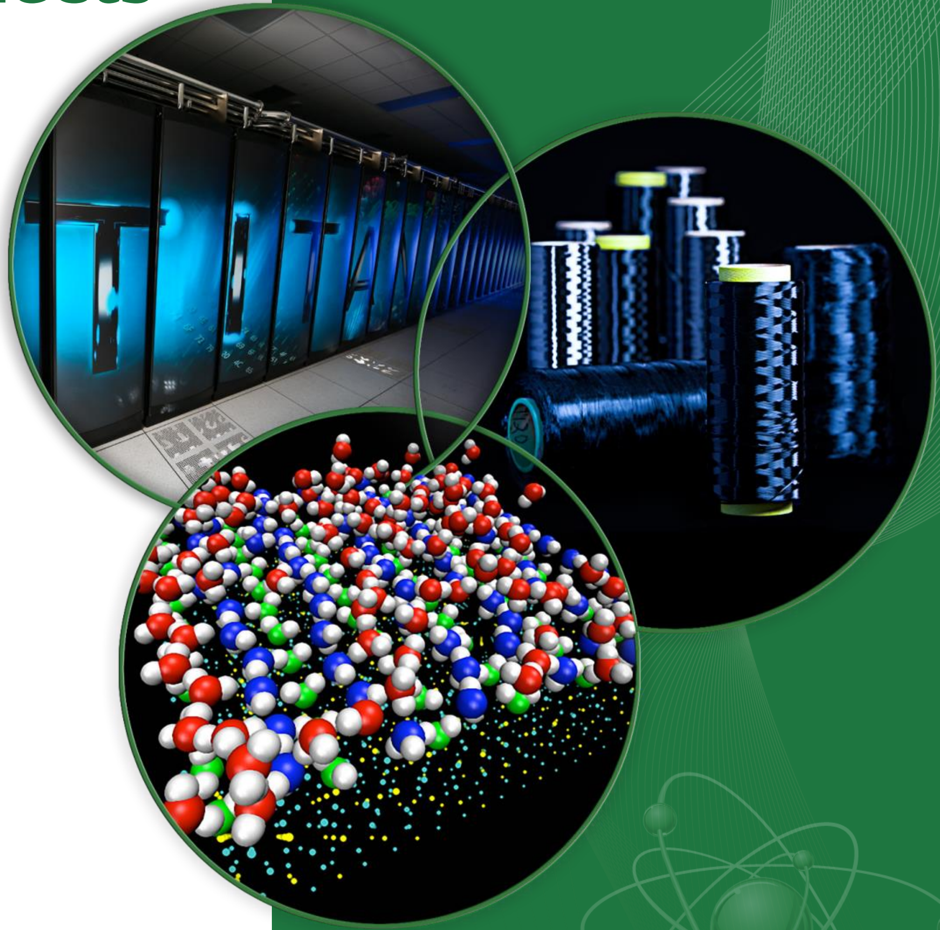
Electromagnetic Environmental Effects for the Power Grid



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April 28, 2016

ORNL is managed by UT-Battelle
for the US Department of Energy

Topics

- The electric grid as complex EM environment
- Beyond EMC: Electromagnetic Environmental Effects (E3)
- E3 technologies and methods
- Selected research directions

Take-Home Message

E3 helps Power Quality (PQ) and Grid Reliability

- EMC-conscious design and testing of power grid components, less disturbances, outages, improving PQ

Smarter Grid, more E3

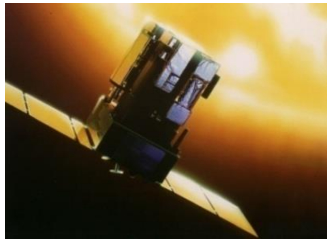
- Fully integrated Smart Grid: co-existence of power lines, sensors, data communication and processing, all requiring stricter E3/EMC guidelines

Need E3

- E3 studies may prevent fixes are generally more costly and less effective than preventive design and testing

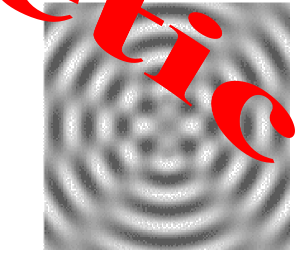
The E3 Context

Electromagnetic Environmental Effects



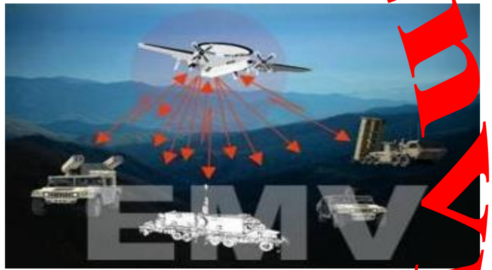
Ionospheric Interactions

EM Compatibility

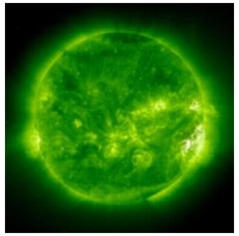


EM Interference

EM Pulse

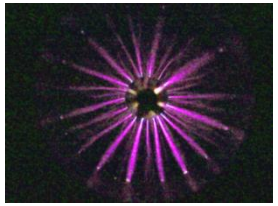


EM Vulnerability



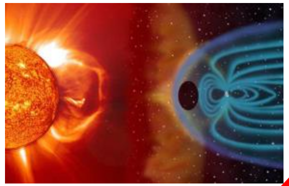
Space
Radiation

EMF Exposure



Electric Discharge

Lightning



GMD

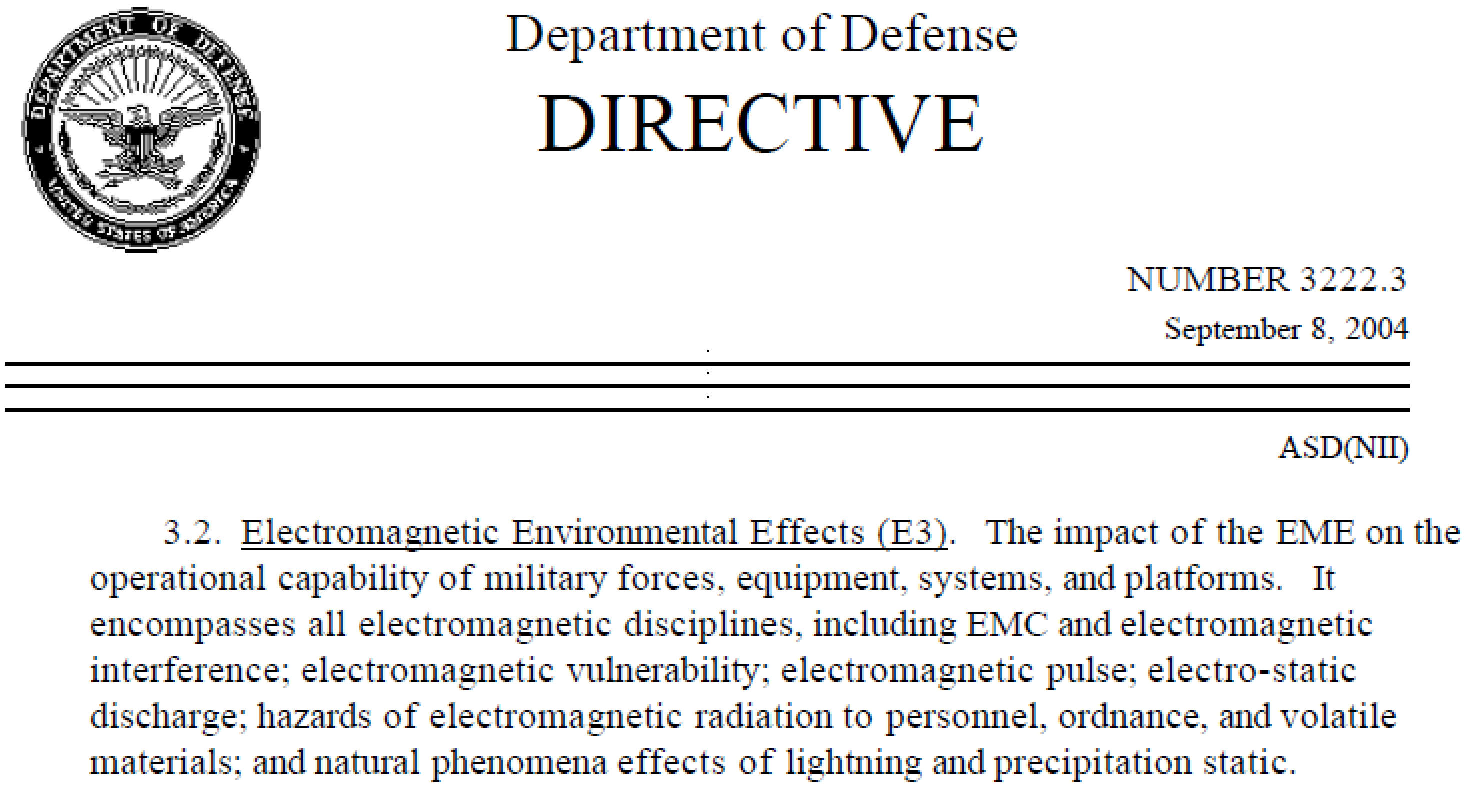
Electromagnetic Environmental Effects (E3)

Definitions

- ***Electromagnetic environment***: resulting from the power and time distribution, in various frequency ranges, of the radiated or conducted electromagnetic emissions

- ***Electromagnetic Environment Effects (*** E^3 ***)***: the impact of the EM environment on the operational capability of equipment and systems. E^3 encompass all electromagnetic disciplines

Electromagnetic Environmental Effects (E3)



Department of Defense

DIRECTIVE

NUMBER 3222.3

September 8, 2004

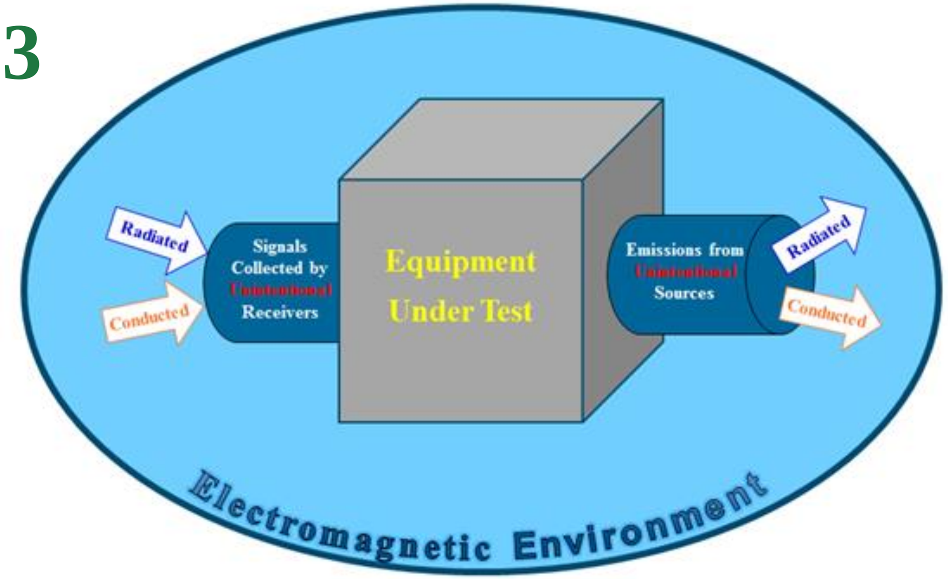
ASD(NII)

3.2. Electromagnetic Environmental Effects (E3). The impact of the EME on the operational capability of military forces, equipment, systems, and platforms. It encompasses all electromagnetic disciplines, including EMC and electromagnetic interference; electromagnetic vulnerability; electromagnetic pulse; electro-static discharge; hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning and precipitation static.

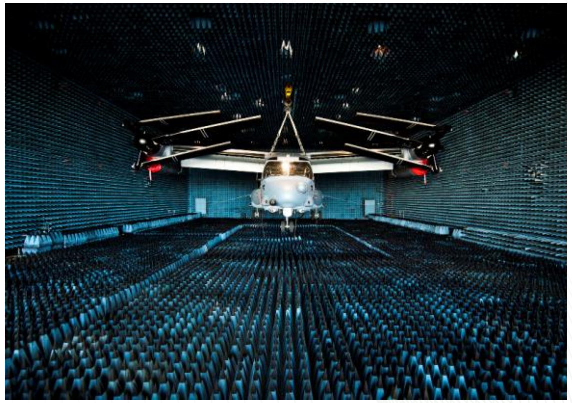
Defining *Electromagnetic Environmental Effects*

Electromagnetic Compatibility is part of E3

- EMC is a far-reaching discipline that affects virtually all applications in the field of electrical engineering.
- EMC is commonly referred to along with electromagnetic interference (EMI):
- EMC and EMI are often interchanged or used together, although they refer essentially to opposite takes on the same issue.



Conceptual sketch of the EMC focus



Anechoic chamber: a typical environment for EMC testing

EMC: the Definition

- Electromagnetic compatibility: “*the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment*” (IEC,1990)
- Following [Paul, 2006], a system is said to be electromagnetically compatible with its environment if the following conditions are met:
  - It doesn’t cause interference with other systems.
  - It is not susceptible to emissions from other systems
  - It doesn’t cause interference with itself

[IEC, 1990] International Electrotechnical Commission, *International Electrotechnical Vocabulary Online*, www.electropedia.org/iev/iev.nsf (1990)

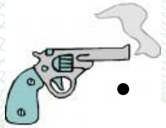
[Paul, 2006] C. A. Paul, *Introduction to Electromagnetic Compatibility* , Wiley (2006)

EMC Relevance to the Electric Utility Sector

EMC Issues Impacting the Power Grid
(PQ=Power Quality, GO=Grid Operations, EU=End-User, GEN=Generation)

Topic	Primary Impact	Possible Example Scenario
Lightning	PQ	Susceptibility (first radiated, then possibly conducted) EMC problem: the source is the lightning, the receptor is or victim in the EMC jargon), the power line
SCADA Components Disturbances	GO	Low-voltage electronics, sensitive to relatively small disturbances, controlling high-power flows
Remote Sensors Disturbances	GO	Monitoring infrastructure relies on a variety of sensors connected to processing electronics and to a signal transmission network (wired or wireless): susceptibility problem of both sensors and data transmission channel
Harmonics on Power Lines	PQ	Proper EMC standard both for nonlinear loads and for sensitive equipment could prevent the problem of the impact of other-than-fundamental frequencies on power conductors
Grid System Level Analysis	PQ	Grid system level EMC analysis: each subsystem provided with emissions and susceptibility requirements to ensure proper functionality.
Power Line Transients	PQ	Example: capacitor bank “ringing”: an EMC approach would provide specialized methods to test tolerance to transients without degrade of performances
New Smart Grid Components	GO	Co-located digital high-speed circuitry, telecommunication devices, and power electronics: increased susceptibility, both conducted and radiated.
Smart Meters Functionality	EU	Impact of conducted emissions from PV inverters on revenue metering.
Home Management System	EU	Surges on mains affecting digital controls for home HVAC and security systems
Power Generation Plant	GEN	Interference/upset of command, control and communication electronics from mobile and fixed wireless devices utilization in a power plant (both nuclear and conventional)
Synchrophasors	GEN	GPS receiver interference affecting the power frequency synchronization

EMC Case Studies



- **Smoking Guns: EMC Case Studies from Electric Utility and Commercial Sources**

EM disturbance in medium voltage switchgear [1]

Amateur Radio Interference from Power Lines [2], [3] and LED Street lights [11]

PLC and Interference among Smart Grid Devices [4]

Interference on telecommunication from ac switching noises [5]

FCC violations from fluorescent lighting [6], [7]

Power line disturbance on railway equipment [8]

FACTS Devices interference with PLC, AM radio and aircraft navigation aids [9]

EMI events in nuclear plants [10]

PQ/EMC Events in Healthcare industry [12]

EMI of PV Systems on AMI [13]

REFERENCES

[1] Burger D. et al., *Proc. 10th Int. Symposium on Electromagnetic Compatibility (EMC Europe 2011), York, UK, September 26-30, 2011*

[2] ARRL EMC Committee Semi-Annual Report (2014)

[3] http://www.arrl.org/fcc-enforcement-activities-and-the-electric-utility-industry

[4] Galli et al., Proc. IEEE v. 99, (6) 998(2011)

[5] Murakawa K. et al., Proc. 2014 Int. Symp. on Electromagnetic Compatibility, Tokyo, Japan, p. 581 (2014)

[6] FCC Citation (2013)

[7] FCC Citation (2014)

[8] CPS EPRI Report

[9] EPRI Report #1008707

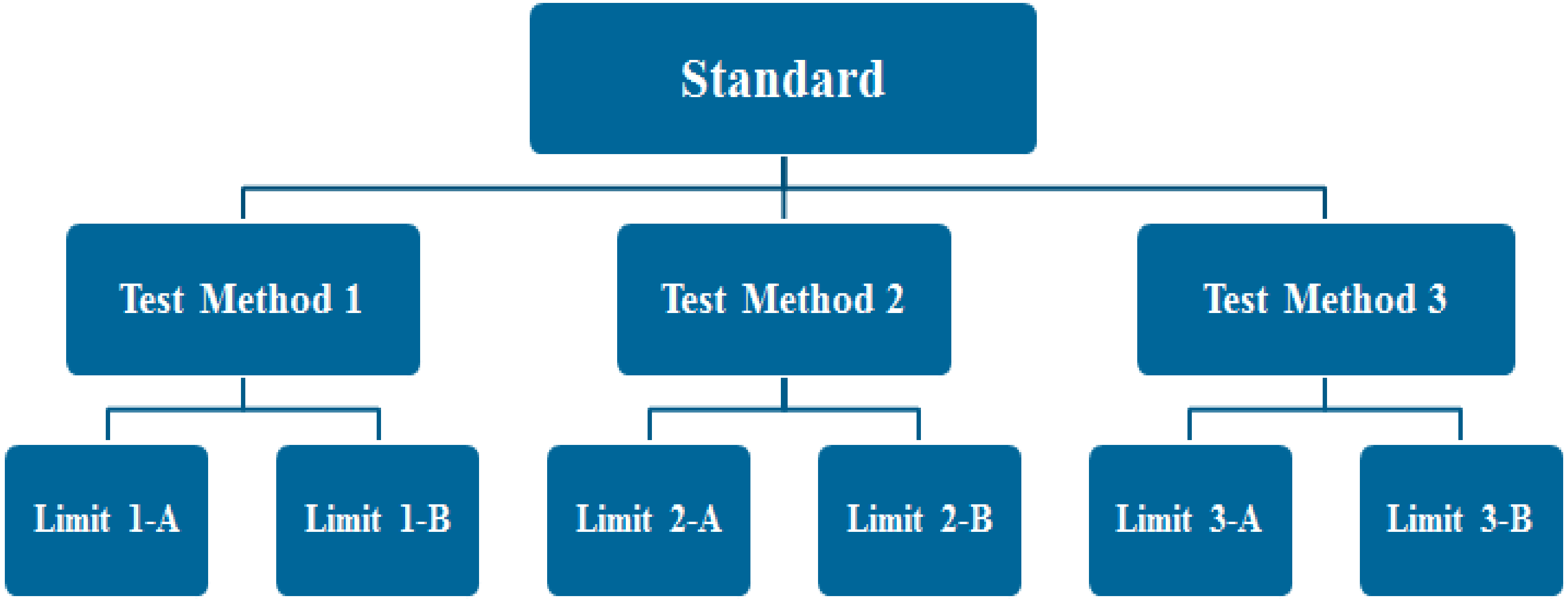
[10] EPRI Report #1008707 (2011)

[11] EPRI Report #1024599 (2011)

[12] EPRI Report TR-113093 (1999)

[13] J. KIRCHHOF, G. KLEIN, Proc. 24th European Photovoltaic Solar Energy Conf., Hamburg, Germany (2009)

Basic Structure of an EMC Standard



- Standard
  - Test Method 1
    - Limit 1-A
    - Limit 1-B
  - Test Method 2
    - Limit 2-A
    - Limit 2-B
  - Test Method 3
    - Limit 3-A
    - Limit 3-B

Generic Specifications for a Test Method for an EMC Standard

Applicability	Describe the type of devices and conditions to which the test applies
Limit	Define the quantities to be measured (typically in volts, amperes, or derived units) and their allowed range
Test procedure	
- Purpose	Describe what the procedure is used for in relation to a particular utilization of the EUT
- Equipment	List the type of test equipment and its defining set of technical specifications (e.g. Spectrum analyzer with 0.1-1000 MHz bandwidth)
- Setup	Geometry and instrumentation placement
- Procedure	Steps necessary to record the required information including preparation phase
- Data presentation	Expected output (plot, table) standardized for easy comparison

EMC Assessment Checklist

Step	Example
Define the assessment scope	“Interference of substation switchgear with wireless temperature sensors”
Define the equipment under test	RX and TX modules of the wireless temperature monitoring system
Define the test location	A substation of choice with high-voltage switchgear. Open-air testing, in situ measurements.
Define the electromagnetic environment	Wideband EM noise. Emissions in the 100 kHz-1 GHz range Transient pulse-train waveform.
Establish a figure-of-merit for the pass/fail criteria (e.g. quantify the degradation of performance)	De-modulated receiver output S/N less than 3 dB
Derive test limits	Placement of the TX sensor module at different distances from the offending source (switchgear hardware) until performance degrades. Collect EM spectrum corresponding to that location
Establish the required diagnostic	Wideband spectrum analyzer with probes covering the required frequency range
Define a test method	See example in Table 1.1

EMC for Grid Power Quality (PQ)

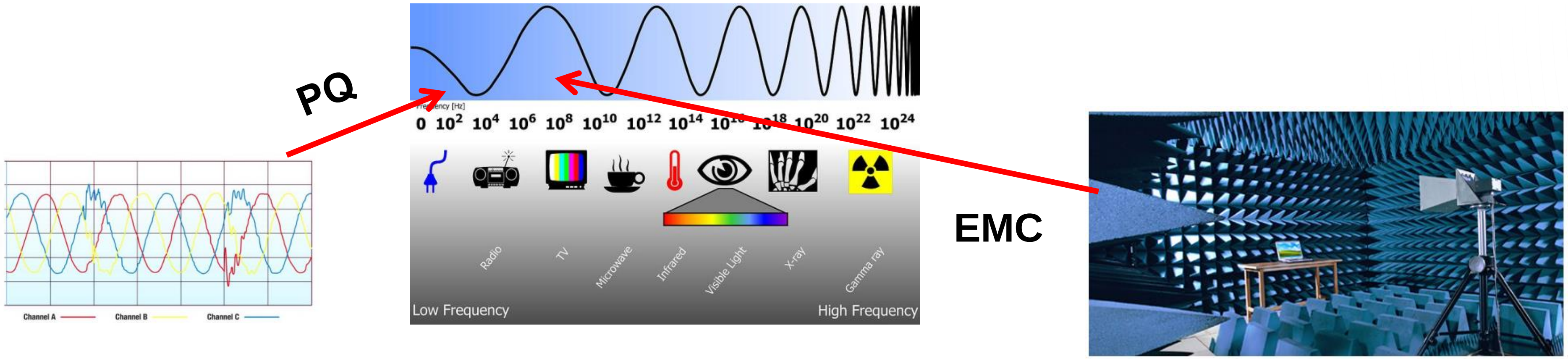
EMC-Related Issues in PQ

- PQ is determined by the “quality” of the voltage waveform made available at the power mains and that EMC
- Focus on how electrical systems and equipment design following EMC principles can positively impact the ability to ensure PQ.
- **PQ Events**
- Typically manifest themselves on the power lines/systems
- Require compatible power levels to be generated

EMC for Grid Power Quality (PQ)

Applying an EMC Perspective to the Power Grid

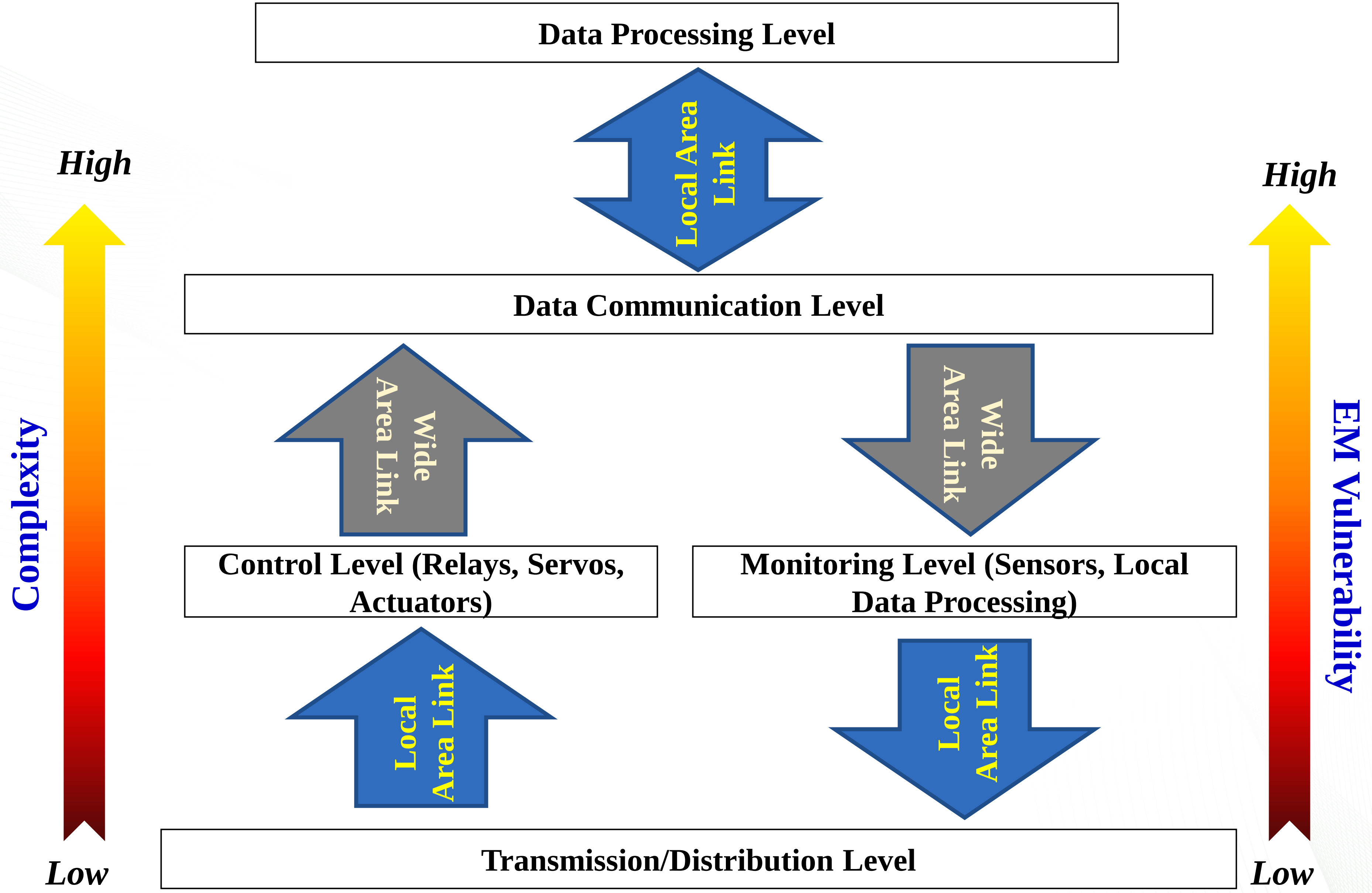
- Systematic approach in determining how grid components can coexist within a given EM environment.
- *intrasystem* electromagnetic compatibility of the power grid considered as a system itself
- Ensuring that components will not be causing mutual interactions affecting negatively the ability of maintaining grid nominal parameters



EMC for Grid Power Quality (PQ)

Example: Lightning strike

- Lightning strike, EMC perspective: inductive coupling to the power lines regarded as a radiated susceptibility problem
- The *source*, the lightning current, is emitting energy that couples inductively to the *receptor*, the power grid line.
- The "radiation" stems from the fact that the coupling path between source and receptor is free space, not a conducting path.



Data Processing Level

Local Area Link

Data Communication Level

Wide Area Link

Wide Area Link

Control Level (Relays, Servos, Actuators)

Monitoring Level (Sensors, Local Data Processing)

Local Area Link

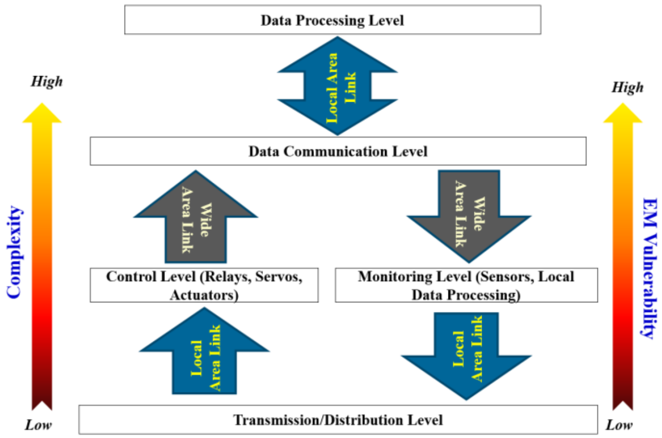
Local Area Link

Transmission/Distribution Level

Power grid multiple technology level components

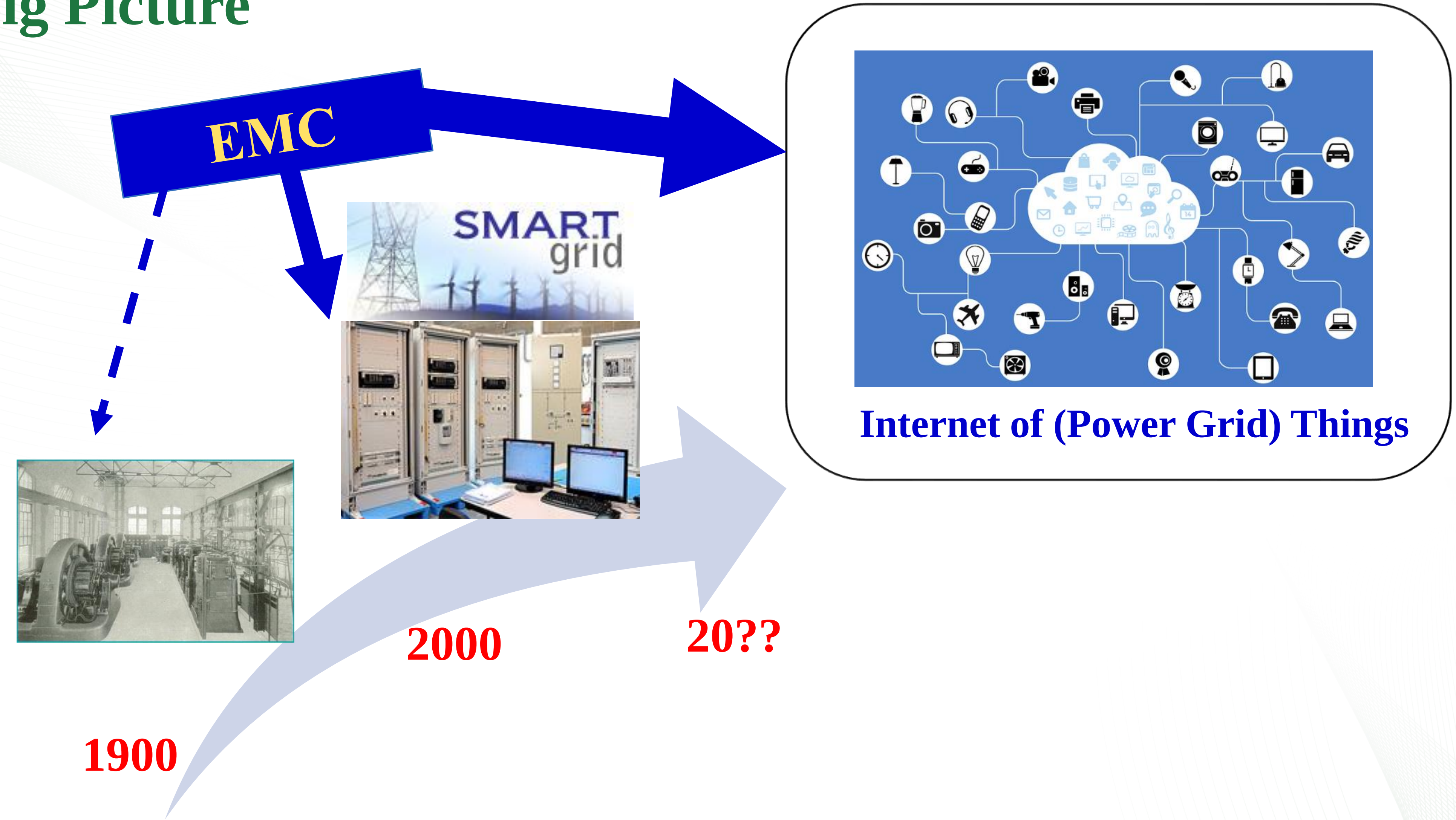
Introduction

- The electric grid is going through a rapid technology transition characterized by a closer integration with power and control electronics, data processing, and telecommunication technologies.
- This process is creating in an increasingly complex electromagnetic environment where large current and voltage components, sensitive electronics, digital signals, and analog waveforms all coexist and interact.
- A growing electronic complexity is also associated, in general, with an increase in vulnerability of the grid to electromagnetic disturbances (EM vulnerability) that can, in turn, compromise the proper functionality of the grid.



Power grid multiple technology level components

The Big Picture



EMC

1900

2000

20??

Internet of (Power Grid) Things

Power grid re-configuration and evolution: new technologies and ***EM C****ompatibility issues*

Electromagnetic Vulnerability

Definition

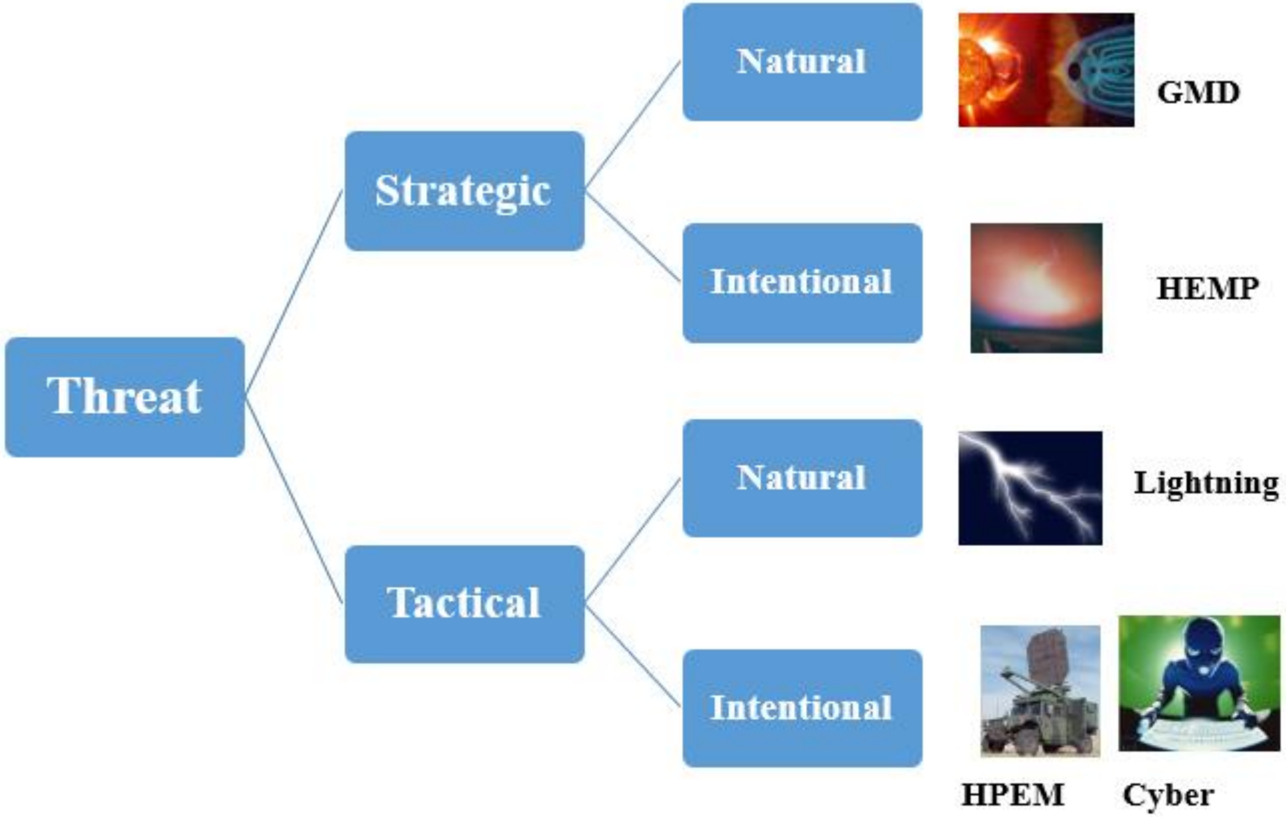
- **Electromagnetic Vulnerability (**EMV): *the characteristics of a system that cause it to suffer a definite degradation (incapability to perform the designated mission) as a result of having been subjected to a certain level of electromagnetic environmental effects.*

  [Joint Chiefs of Staff Publication No. 1-02, DoD Dictionary of Military and Associated Terms http://www.dtic.mil/doctrine/jel/doddict/ - (2007)]

- EMV can be considered part of the susceptibility side of EMI, for situations where susceptibility causes unacceptable system performance issues of failures
- A system is said to be *EM vulnerable* if its performance is degraded below a satisfactory level as a result of exposure to an EM field (typically in reference to system safety exploitable by enemy forces).

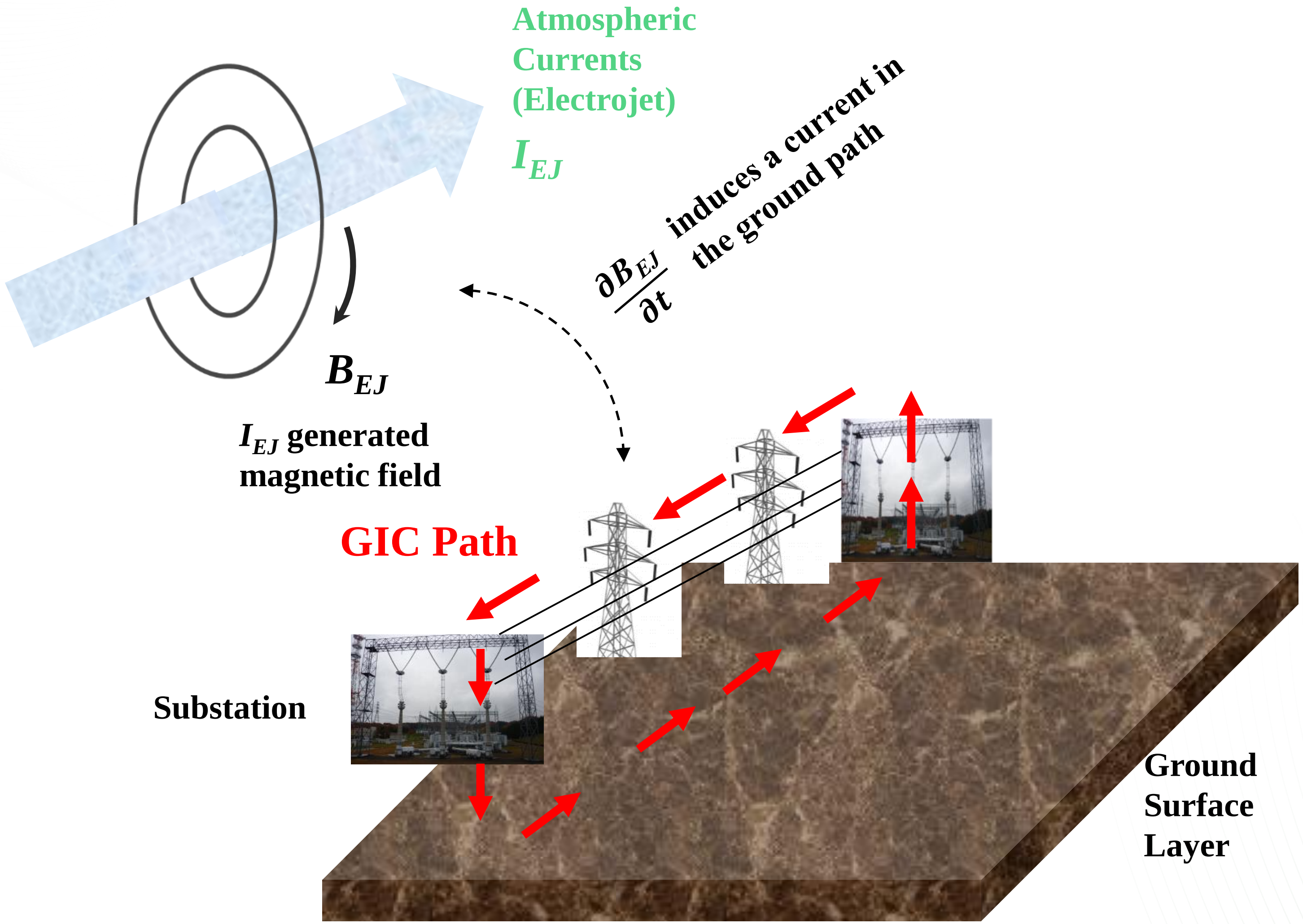
Power Grid Electromagnetic Vulnerability

- Threat analysis and countermeasures for protection of critical assets
- Modeling the impacts of large geomagnetic activity due to “space weather” events on transformers and critical grid infrastructures



Threat
Strategic
Tactical
Natural
Intentional
Natural
Intentional
GMD
HEMP
Lightning
HPEM
Cyber

Impact of Geomagnetic Storms on the Power Grid



Atmospheric
Currents
(Electrojet)
I_{EJ}

$\frac{\partial B_{EJ}}{\partial t}$ induces a current in the ground path

B_{EJ}

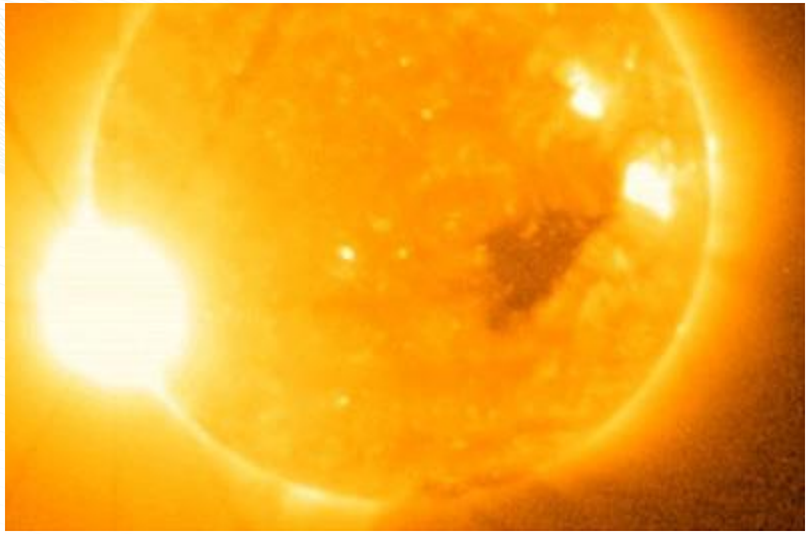
I_{EJ} generated
magnetic field

GIC Path

Substation

**Ground
Surface
Layer**

The Effects of Solar Flares on Electric Power Systems



- Solar flare striking Earth is mainly confined to the low-Earth orbit and ionosphere.
- Long-range radio and satellite-based communication can be affected.
- A flare may be associated with an Earth-bound coronal mass ejection, that may be lead to a geomagnetic storm impacting the electric power grid.

- Synchronization of electric power-generation plants that supply the grid increasingly relies on GPS-based
- GPS reference is also used to identify with high-precision fault locations on power lines, reducing the time required to restore power.
- If a large solar flare disrupts the GPS service, the synchronization of power generation has to revert to the older technology, which is based on local sensors, resulting, at best, in reduced efficiency

Smarter Grid, Increased EM Vulnerability

Control Centers and SCADA systems:

- Vulnerability from sensors triggering relays (microprocessor-based relay architecture)
- Electronic chip damages (microprocessors, PLC’s

Distribution

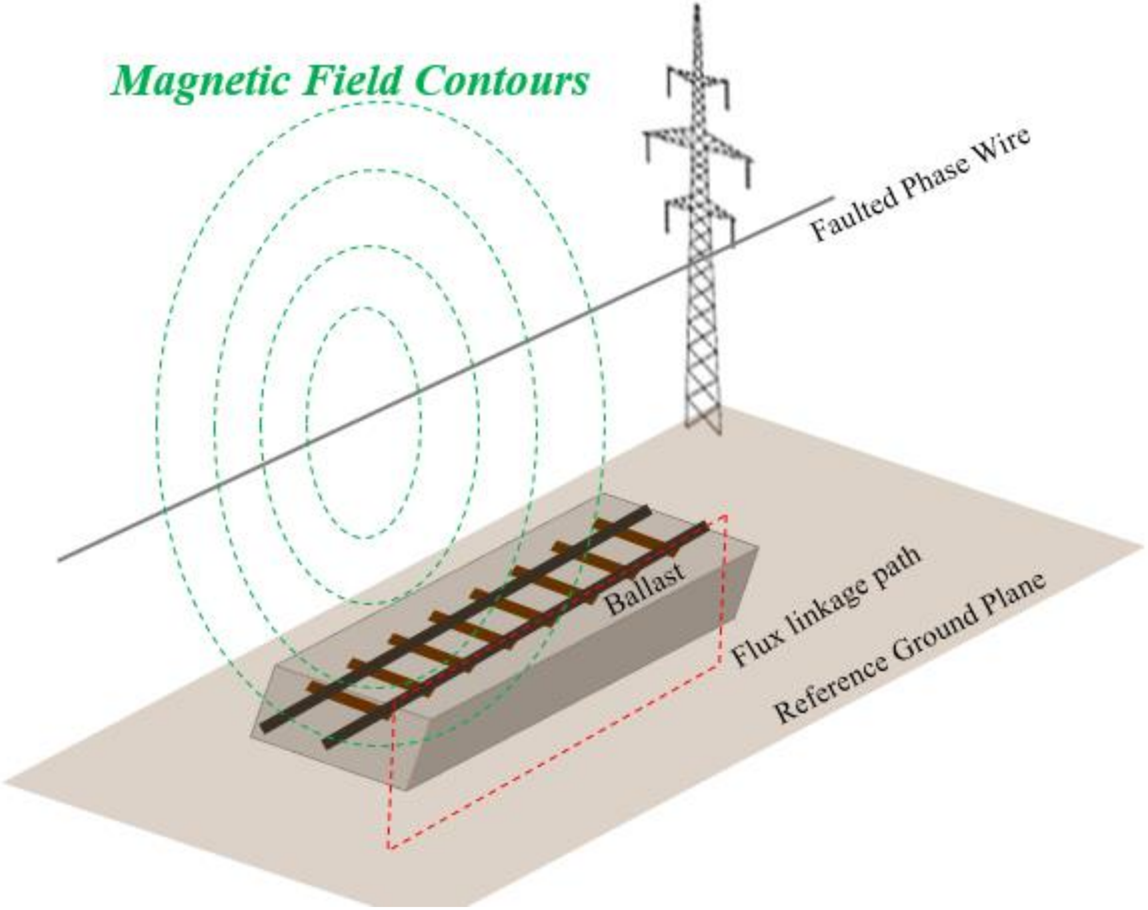
- Lines Flashovers
- Transformers
- Tests performed at ORNL on E1 pulse types show damage of typical step-down transformers

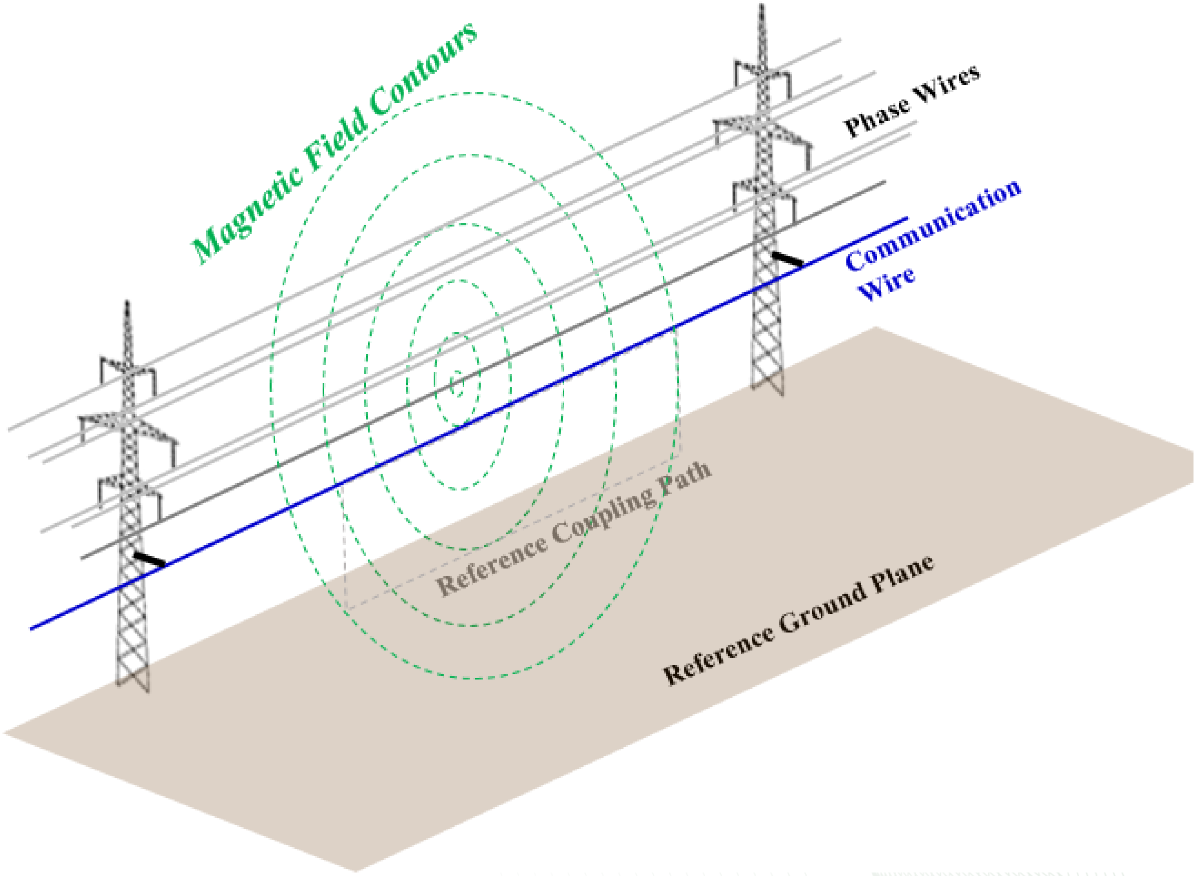
Interface module for substation breakers and reclosers

Total Substation Automation Solutions

Programmable automation controller (PAC) for substations

EM Coupling of Power Lines to Railways and Surface Conductors





Lightning Protection Studies

- Lightning strikes impacting transmission lines, causing outages and other damage on the electrical grid
- Shield wires are often installed in pairs on top of transmission towers, but they offer only limited protection, especially during a “side strike.”
- Modeling of direct and indirect effects and attachment patterns
- Electro-geometric analysis for protection of structures and provide guidelines for new designs.

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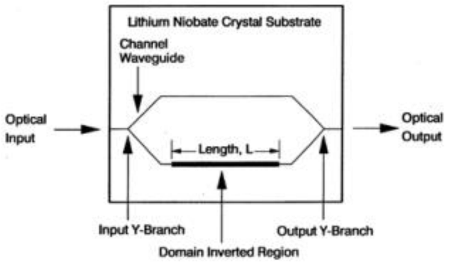
Electric Discharge Comprehensive Monitoring/Detection

- Unwanted electric discharges may occur due to environmental conditions, component failure, dielectric fatigue
- Discharges may cause EMI, equipment failure, fire ignition
- A partial discharge may be a precursor of an insulation breakdown of high voltage equipment
- Testing of equipment design and layout should can ensure a discharge-free environment both in normal and emergency operating conditions

Sensors for Power Transmission and Distribution

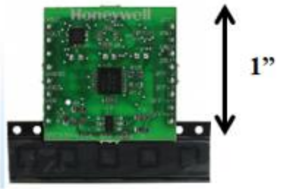
Electric Field Optical Sensor (SRICO)

- Optical chip, electrode-less, non-metallic sensor head
- Frequency Range 1 Hz to 2 GHz
- E-Field Range 1 V/m to 5 kV/m
- Damage Threshold > 10 MV/m

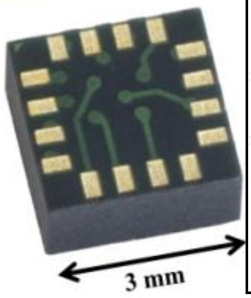


Magnetic Field (Honeywell)

- HMC1043: miniature three-axis surface mount sensor
- High-sensitivity, low-field magnetic sensor
- Anisotropic Magnetoresistive (AMR) technology
- 5 MHz bandwidth



HMC 1043 demo board (1"x1")



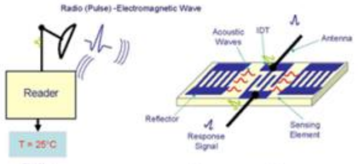
HMC 1043 sensor

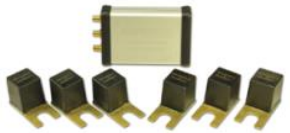
Current Optical Sensor (PowerSense A/S)

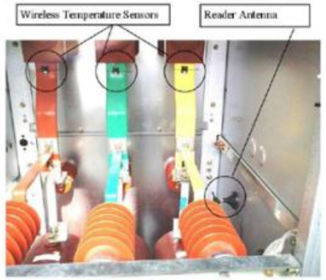
- Faraday rotation current sensor
- Current range 5-20,000 AAC

Temperature Sensor (Vectron International)

- TempTrackr™ System for Smart Grid Power Distribution Applications for continuously monitor temperature
- Surface Acoustic Wave (SAW) resonators passive wireless sensing



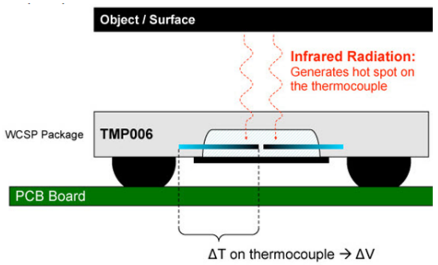


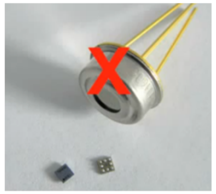


Installation into a 10-15kV switchbox

Temperature Sensor (Texas Instruments)

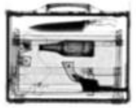
- TMP006 Thermopile: first single-chip digital IR MEMS temperature sensor
- 90% lower power consumption and are more than 95% smaller than existing solutions

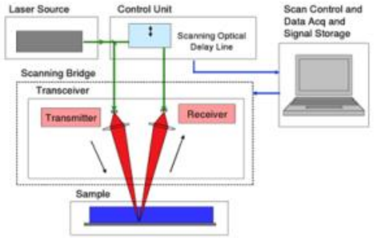




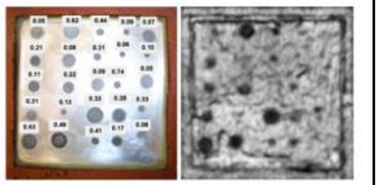
THz Non-Destructive Evaluation of Materials

- THz (millimeter waves) imaging through dielectric materials (imaging also widely used at airport security)
- Used for years in aerospace for NDE





THz imaging schematic

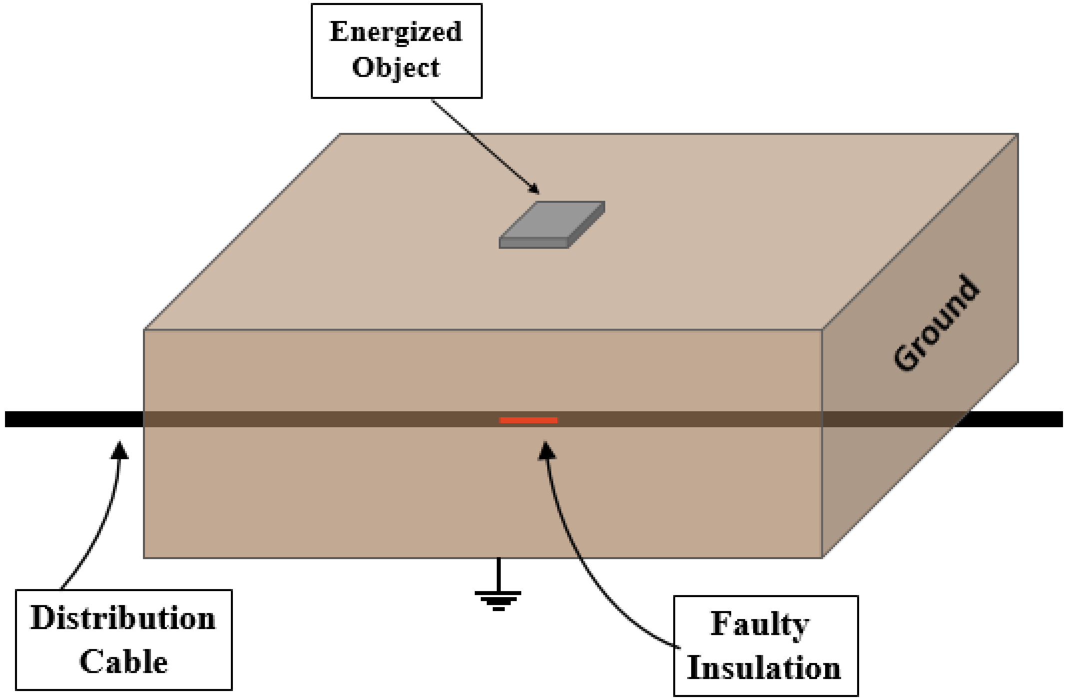


NASA Shuttle tile corrosion experiment

Power Line Energized Objects in Urban Environment

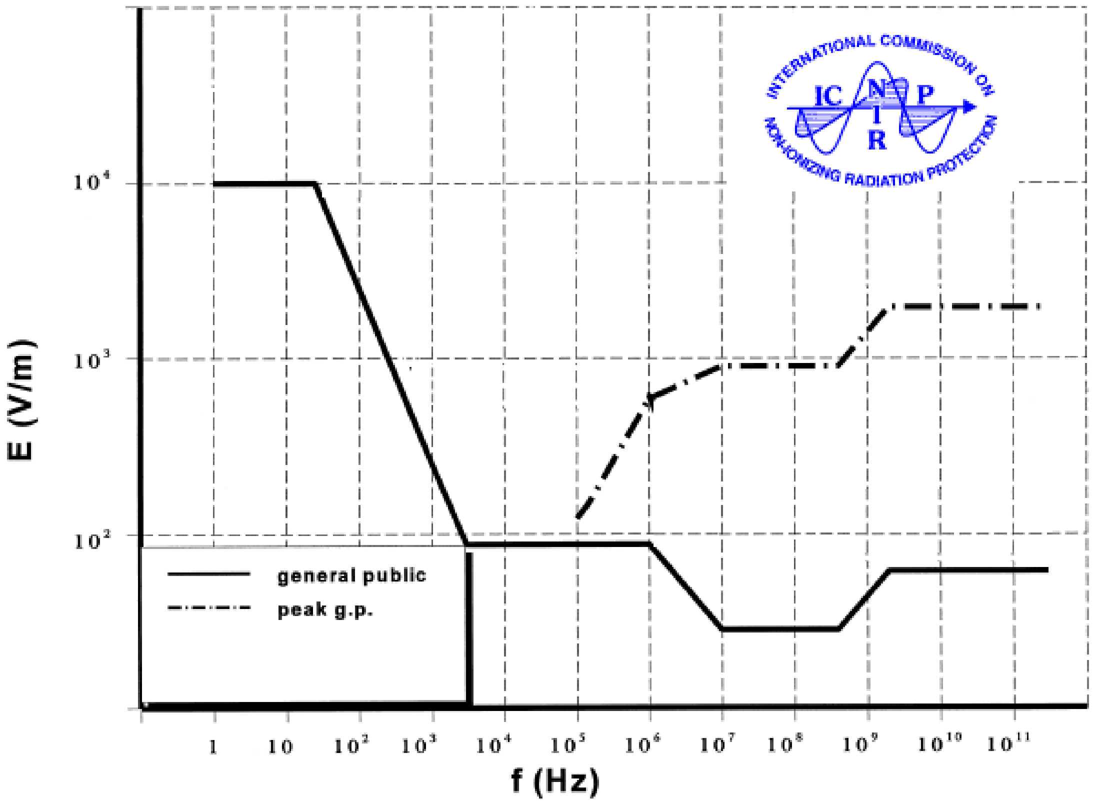
- Objects may become energized due to contact with faulty insulation wiring either directly in contact with the objects or in their immediate vicinity.

- The energized object may be part of a much larger conducting volume, exhibiting large conductivity variations, from case to case, depending on the local characteristic of the soil, the presence of underground structures (e.g. pipelines) and the moisture level.

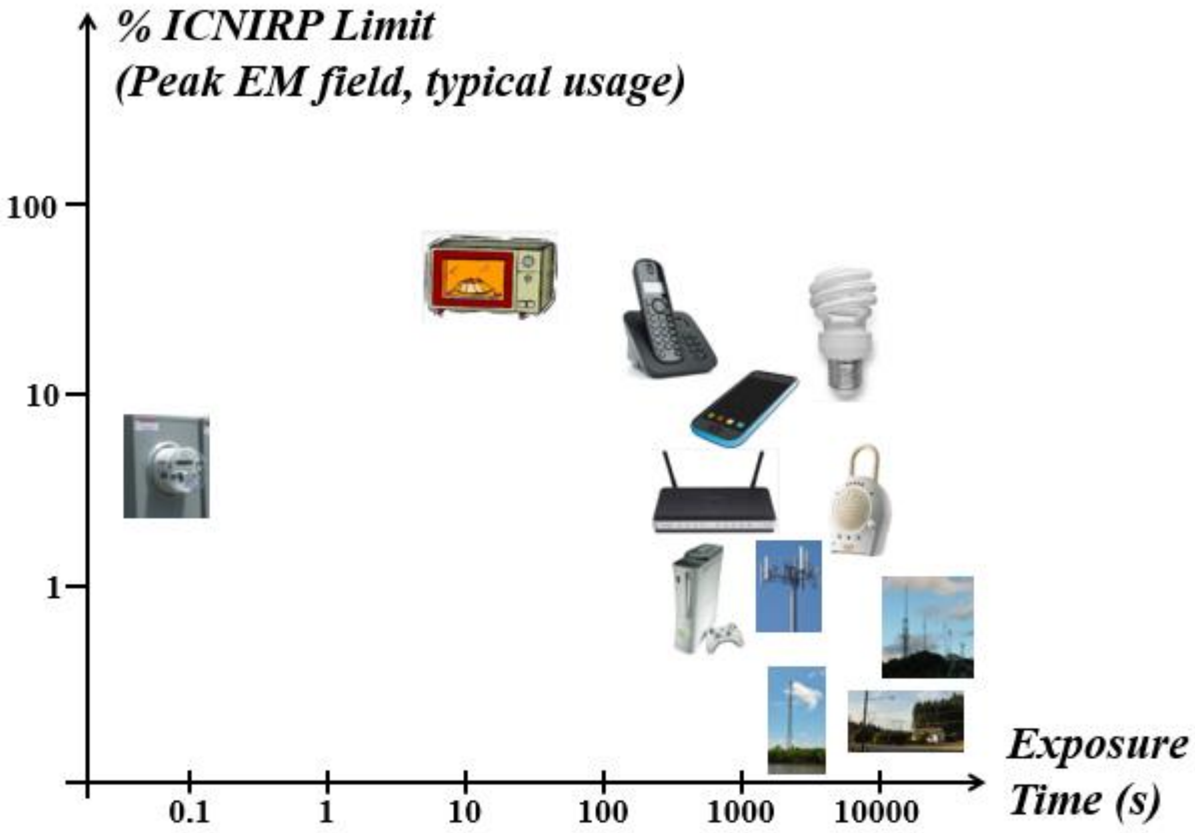


Object Energized through Underground Conductor Fault

Characterization of Human to EM Exposure Emissions



“Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz)”. Health Phys. 74, 494, 1998.

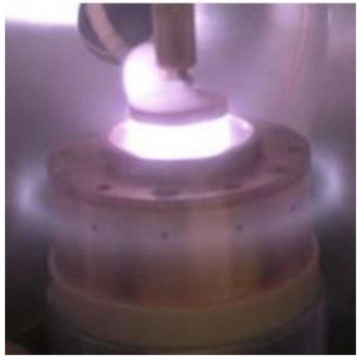


Qualitative comparison of EM emissions for different sources present in common households vs. typical exposure time (both axes are on a logarithmic scale).

Modeling & Simulation

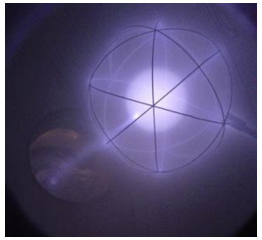
Geomagnetic Induced Currents

Lightning



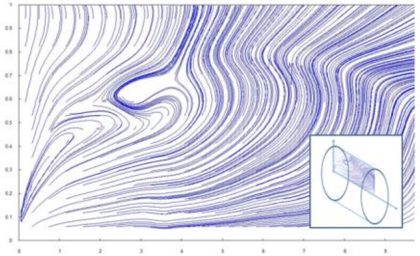
Advanced plasma switch (DoE/PPPL and General Electric)

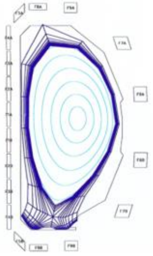
Fusion Energy



Magnetohydrodynamic (MHD) Plasma Simulation

- MHD Power generation
- HV Switchgear Arc flash, Lightning
- Geomagnetic disturbances
- MHD Power generation
- Nuclear Fusion Energy Research





What is Magnetohydrodynamics?

- Magnetohydrodynamics models a plasma as a fluid overall neutral, but consisting of separate charged particle species and that responds to EM forces
- The Navier-Stokes equation for an ordinary, non-viscous fluid dominated by collisions is

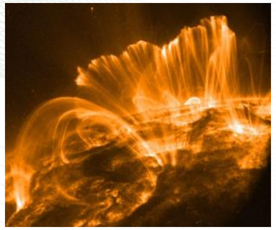
$$\rho\left[\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right]=-\nabla p$$

where $\rho=mn$

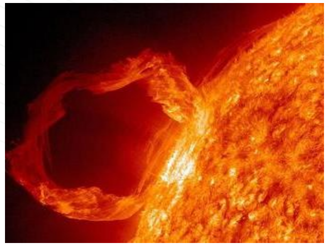
- For a plasma, the EM force term is added, obtaining the magnetohydrodynamic momentum equation

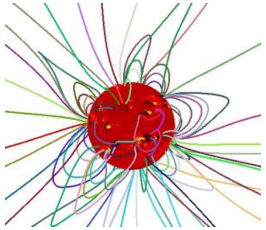
$$nm\left[\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right]=qn(\mathbf{E}+\mathbf{u}\times\mathbf{B})-\nabla p$$

Geomagnetic Induced Currents (GIC's)

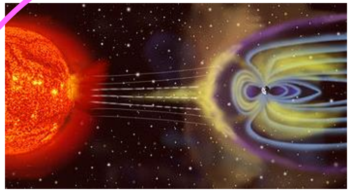


Solar Plasma Observation



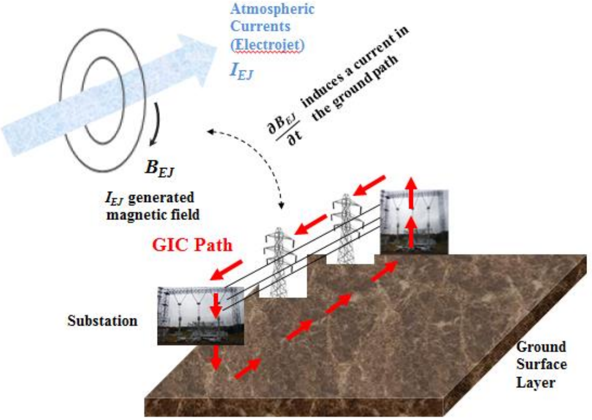


Solar Activity Modeling



Sun-Magnetosphere Interaction

Currently underdeveloped link



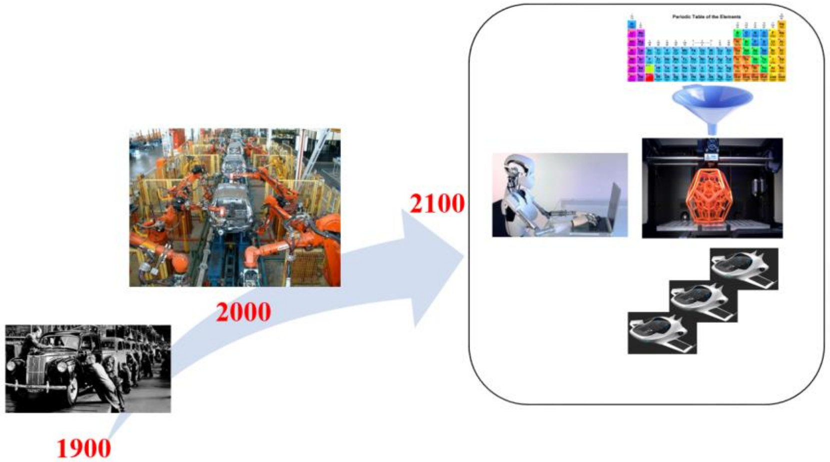
Modeling the GIC

Modeling Disruptive Grid Events

Towards integrated computer modeling for forecasting grid-impact of solar events

New Loads: Advanced Manufacturing

- **Advanced Manufacturing (AM):** *a complex and integrated set of automatic production processes relying on information technology, utilizing recently developed technologies and/or materials, characterized by high energy efficiency, and minimal waste and overall environmental impact*
- *"**Smart Factory**": encompasses the integration of sensors, robotics, electrotechnologies, energy efficiency, power quality*



AM from the Power Grid perspective

- Increased need for a constant load during more hours of the day (load-leveling effect)
- Less power required overall (A.M., through use of electronics and process optimization is naturally geared towards energy efficiency)
- More *microgrids* and power conditioning to protect critical processes
- Increased need of DC power

EMI and PV Generation


SC 77A

Harmonic Current Disturbances 2-150 kHz

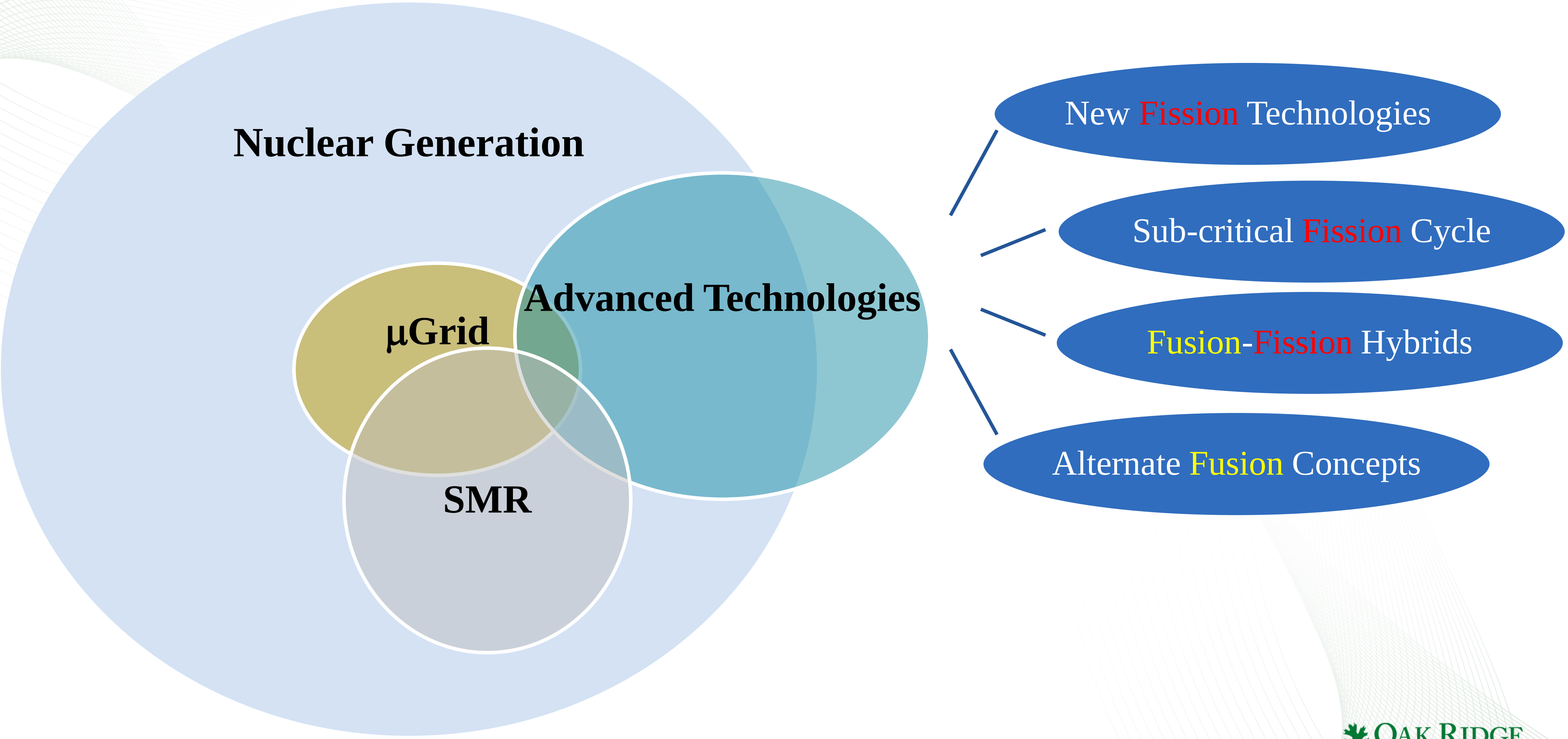
Overview on Issues with Smart Meters

Raimond Bauknecht
Landis + Gyr
11. April 2011
CESI Milan

Technical Committee
SC 77A WG 6
LOW FREQUENCY IMMUNITY TESTS

- First anomalies reported in Germany in 2007 with PV inverters and electronic meters
- Fraunhofer ISET investigations in 2009/2010 confirm irregular behavior of some meter types with PV inverters. A gap in standardization for both emission and immunity in the frequency range 2 – 150 kHz was identified.
- Fraunhofer ISET developed an immunity test for electronic meters. Some German utilities require passing this test in their product acceptance procedures since early 2010. Other institutes have developed similar tests.
- In 2010 discussion about this topic started in several international regulation committees such as IEC and CENELEC.

Research Directions: Nuclear Generation

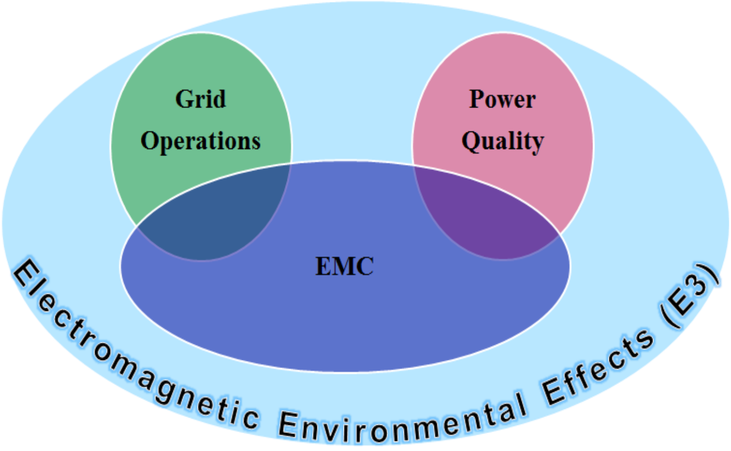


- New Fission Technologies
- Sub-critical Fission Cycle
- Fusion-Fission Hybrids
- Alternate Fusion Concepts

Research Directions: Nuclear Generation

- The paradigm of large, centralized, power station is changing in favor of distributed energy resources and microgrids
- Currently mostly for renewables, this trend is also impacting the nuclear industry as small modular reactors (SMR, nuclear reactors, that is) are being developed and become economically competitive
- New technologies, as compared to standard Light Water Reactor (LWR) technology may lead to more even compact, low-maintenance, factory-built/serviced units
- SMR economics: local microgrid loads may be too small => need to sell power on the main grid

Conclusions



- A fundamental contribution that can be derived from applying an E3 perspective to the power grid is a systematic approach in determining how grid components can coexist within a given electromagnetic environment.
- The EMC classification of disturbances provides a practical and well-tested approach for the monitoring and diagnostics of the complex environment
- A solid reference standard is needed for smart-grid engineering practices would flow naturally from an electromagnetic environmental effects (E3) perspective applied to the power grid seen as a complex system
- Power Quality becomes the reference goal that provides a metric for the application of EMC standards.