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Power Quality and Smart Grid

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Outline

- Power Quality:
  - What is PQ?
  - Typical PQ Disturbances
  - Impact on Power Equipment
  - Standards
  - Instrumentation
  - Economic Impact
- Smart Grid:
  - What is SG?
  - Vision, Drivers, Stakeholders
  - Characteristics of SG
  - Comparison CG and SG
  - Jobs, Investments, Priorities
  - Examples and Sensors
- Conclusion
- Acknowledgement

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Power Quality

Slide 3 <optional info>

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What is Power Quality?

- The term *power quality* seems ambiguous. It means different things to different people. So, what is power quality?

- Is power quality a problem or a product? It depends on your perspective.

- If you are an electrical engineer, power quality expert, etc. →→→ problem that must be solved.

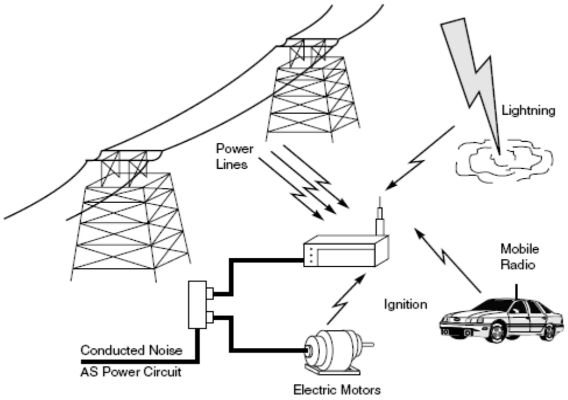
- If you are a power marketer, or purchaser of electrical power, etc. →→→ product and power quality as an important part of that product.

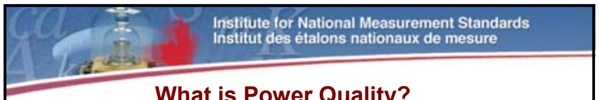
What is Power Quality?

- IEEE Std 1100-1999:
  "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment."

- IEC 61000-1-1 in line with IEEE Std 1100-2005:
  "the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances".

Some factors affecting electromagnetic compatibility





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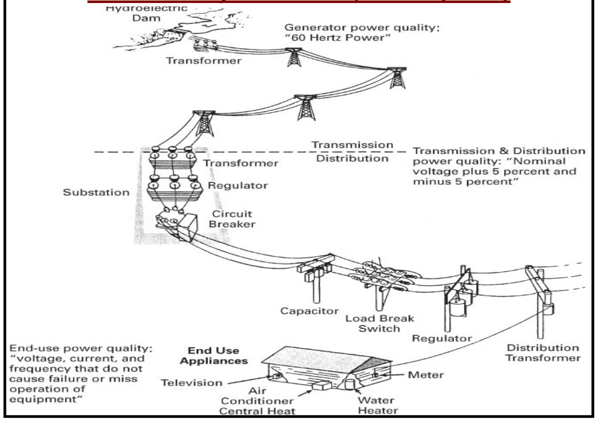
What is Power Quality?

- Power quality is ultimately a consumer-driven issue, and the end user's point of reference takes precedence. Therefore, the following power quality problem definition would be more appropriate:

- Any power problem manifested in voltage, current, or frequency deviations that results in failure or miss-operation of customer equipment.

Power Quality Definitions (*Courtesy BPA)*



Generator power quality: "60 Hertz Power"

Transmission & Distribution power quality: "Nominal voltage plus 5 percent and minus 5 percent"

End-use power quality: "voltage, current, and frequency that do not cause failure or miss operation of equipment"

Power Quality ≈ Voltage Quality

- Power quality is actually the quality of the voltage that is being addressed in most cases.

- The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw.

- Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits.

Power Quality ≈ Voltage Quality (Cont.)

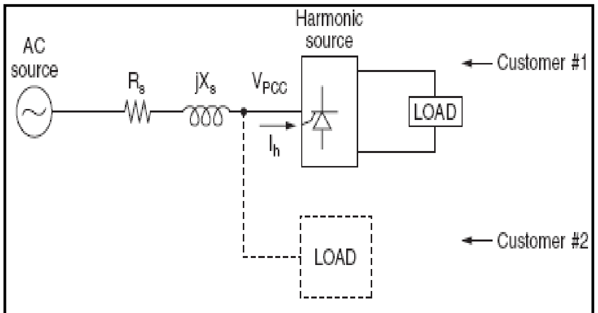
- Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage.

- A major part of the impedance in a power system comes from overhead lines and transformers. This power equipment usually belongs to utilities, and thus they have control over the impedance.

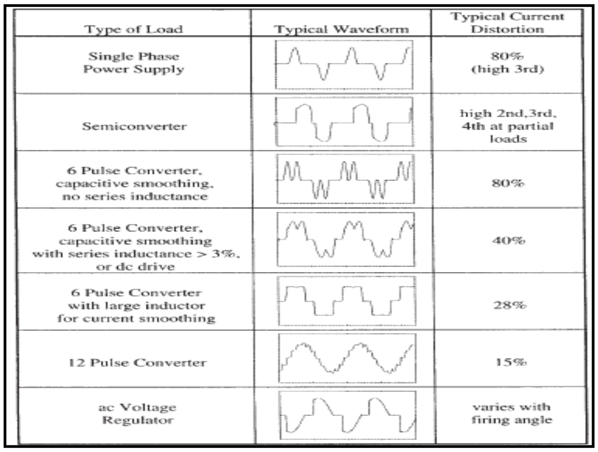
Power Quality ≈ Voltage Quality (Cont.)

- However, end-users have control over currents since their equipment draw currents from the system.

- Therefore, in studying power quality, it is very important to understand the characteristics of utility impedance and also currents drawn by end-user equipment.

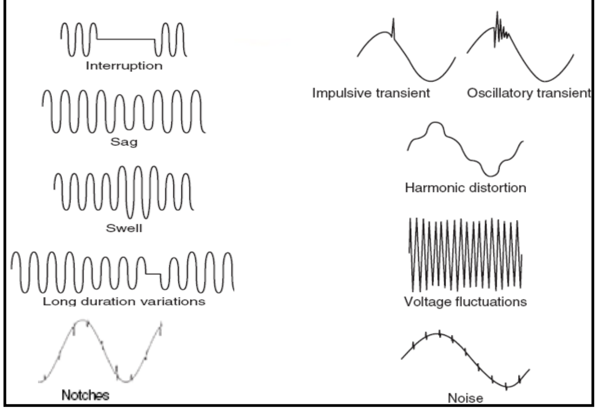


- Harmonic-generating load causing voltage distortion at the point of common coupling (PCC). The AC source is modeled as an ideal voltage source in series with a resistance *Rs* and a reactance *jXs*.



Type of Load	Typical Waveform	Typical Current Distortion
Single Phase Power Supply		80% (high 3rd)
Semiconverter		high 2nd,3rd, 4th at partial loads
6 Pulse Converter, capacitive smoothing, no series inductance		80%
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%
6 Pulse Converter with large inductor for current smoothing		28%
12 Pulse Converter		15%
ac Voltage Regulator		varies with firing angle

Typical Power Disturbances



Effects of Harmonics on Equipment

Equipment	Harmonic effects	Results
Capacitors	- Capacitor impedance decreases with increasing frequency, so capacitors act as sinks where harmonics converge; capacitors do not, however, generate - Supply system inductance can resonate with capacitors at some harmonic frequency, causing large currents and voltages to develop - Dry capacitors cannot dissipate heat very well, and are therefore more susceptible to damage from harmonics - Breakdown of dielectric material - Capacitors used in computers are particularly susceptible, since they are often unprotected by fuses or relays - As a general rule of thumb, untuned capacitors and power switching devices are incompatible	- Heating of capacitors due to increased dielectric losses - Short circuits - Fuse failure - Capacitor explosion

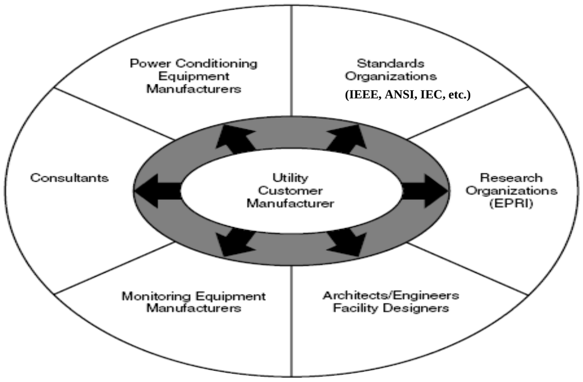
Effects of Harmonics on Equipment (Cont.)

Equipment	Harmonic effects	Results
Transformers	- Voltage harmonics cause higher transformer voltage and insulation stress; normally not a significant problem	- Transformer heating - Reduced life - Increased copper and iron losses - Insulation stress - Stress
Motors	- Increased losses - Harmonic voltages produce magnetic fields rotating at a speed corresponding to the harmonic frequency	- Motor heating - Mechanical vibrations and noise - Pulsating torques - Increased copper and iron losses in stator and rotor windings, from 5–10% - Reduced efficiency - Reduced life - Voltage stress on insulation of motor windings

Effects of Harmonics on Equipment (Cont.)

Equipment	Harmonic effects	Results
Electromechanical induction disk relays	- Additional torque components are produced and may alter the time delay characteristics of the relays	- Incorrect tripping of relays - Incorrect readings
Circuit breakers	- Blowout coils may not operate properly in the presence of harmonic currents	- Failure to interrupt currents - Breaker failure
Watt-hour meters, overcurrent relays	- Harmonics generate additional torque on the induction disk, which can cause improper operation since these devices are calibrated for accurate operation on the fundamental frequency only	- Incorrect readings
Electronic and computer-controlled equipment	- Electronic controls are often dependent on the zero crossing or on the voltage peak for proper control; however, harmonics can significantly alter these parameters, thus adversely affecting operation	- Maloperation of control and protection equipment - Premature equipment failure - Erratic operation of static drives and robots

Relationship of organizations involved in power quality



Power Conditioning Equipment Manufacturers

Standards Organizations
(IEEE, ANSI, IEC, etc.)

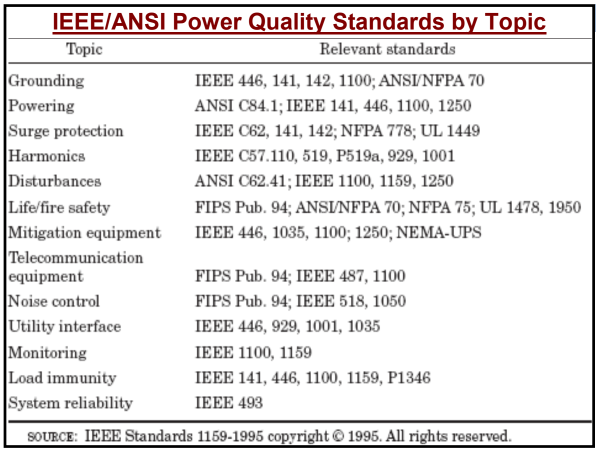
Consultants

Utility
Customer
Manufacturer

Research Organizations (EPRI)

Monitoring Equipment Manufacturers

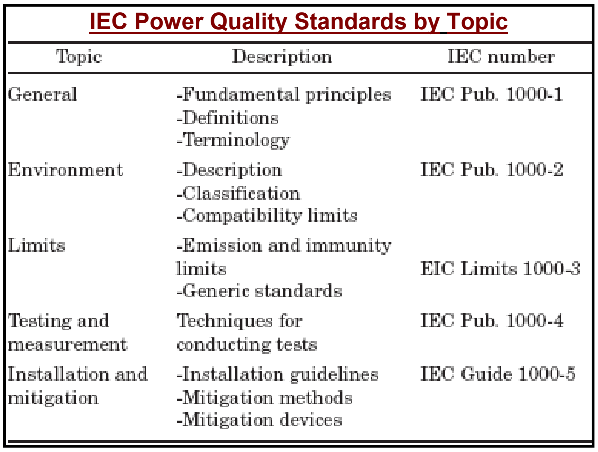
Architects/Engineers
Facility Designers



IEEE/ANSI Power Quality Standards by Topic

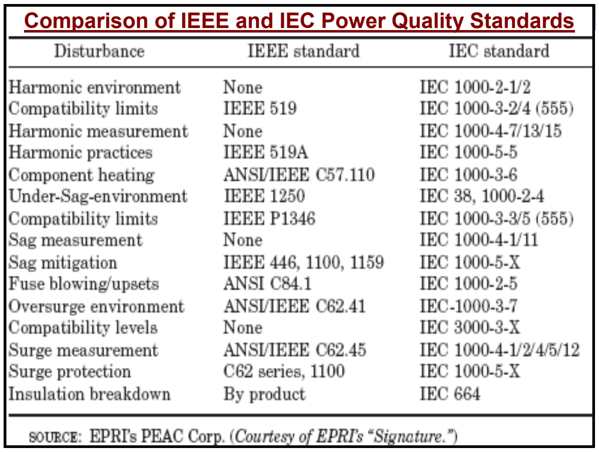
Topic	Relevant standards
Grounding	IEEE 446, 141, 142, 1100; ANSI/NFPA 70
Powering	ANSI C84.1; IEEE 141, 446, 1100, 1250
Surge protection	IEEE C62, 141, 142; NFPA 778; UL 1449
Harmonics	IEEE C57.110, 519, P519a, 929, 1001
Disturbances	ANSI C62.41; IEEE 1100, 1159, 1250
Life/fire safety	FIPS Pub. 94; ANSI/NFPA 70; NFPA 75; UL 1478, 1950
Mitigation equipment	IEEE 446, 1035, 1100; 1250; NEMA-UPS
Telecommunication equipment	FIPS Pub. 94; IEEE 487, 1100
Noise control	FIPS Pub. 94; IEEE 518, 1050
Utility interface	IEEE 446, 929, 1001, 1035
Monitoring	IEEE 1100, 1159
Load immunity	IEEE 141, 446, 1100, 1159, P1346
System reliability	IEEE 493

SOURCE: IEEE Standards 1159-1995 copyright © 1995. All rights reserved.



IEC Power Quality Standards by Topic

Topic	Description	IEC number
General	-Fundamental principles -Definitions -Terminology	IEC Pub. 1000-1
Environment	-Description -Classification -Compatibility limits	IEC Pub. 1000-2
Limits	-Emission and immunity limits -Generic standards	EIC Limits 1000-3
Testing and measurement	Techniques for conducting tests	IEC Pub. 1000-4
Installation and mitigation	-Installation guidelines -Mitigation methods -Mitigation devices	IEC Guide 1000-5



Comparison of IEEE and IEC Power Quality Standards

Disturbance	IEEE standard	IEC standard
Harmonic environment	None	IEC 1000-2-1/2
Compatibility limits	IEEE 519	IEC 1000-3-2/4 (555)
Harmonic measurement	None	IEC 1000-4-7/13/15
Harmonic practices	IEEE 519A	IEC 1000-5-5
Component heating	ANSI/IEEE C57.110	IEC 1000-3-6
Under-Sag-environment	IEEE 1250	IEC 38, 1000-2-4
Compatibility limits	IEEE P1346	IEC 1000-3-3/5 (555)
Sag measurement	None	IEC 1000-4-1/11
Sag mitigation	IEEE 446, 1100, 1159	IEC 1000-5-X
Fuse blowing/upsets	ANSI C84.1	IEC 1000-2-5
Oversurge environment	ANSI/IEEE C62.41	IEC-1000-3-7
Compatibility levels	None	IEC 3000-3-X
Surge measurement	ANSI/IEEE C62.45	IEC 1000-4-1/2/4/5/12
Surge protection	C62 series, 1100	IEC 1000-5-X
Insulation breakdown	By product	IEC 664

SOURCE: EPRI's PEAC Corp. (*Courtesy of EPRI's "Signature."*)

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2 Important IEEE Standards for Revenue Metering

- **IEEE 519-1992**,
  Recommended Practices and Requirements for Harmonic Control in Electric Power Systems
- **IEEE Std 1459TM-2010,**
  Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Non-sinusoidal, Balanced, or Unbalanced Conditions

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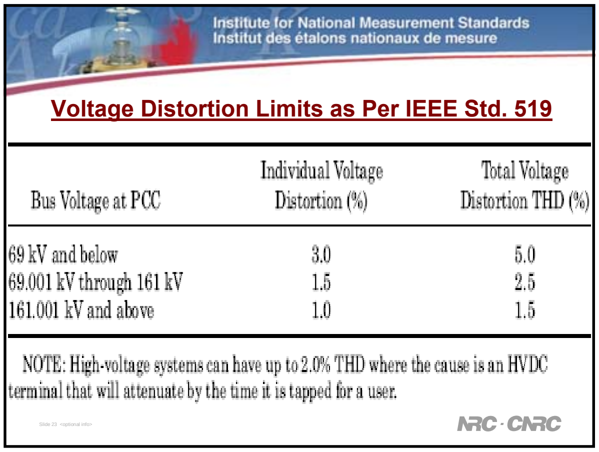

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Voltage Distortion Limits as Per IEEE Std. 519

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

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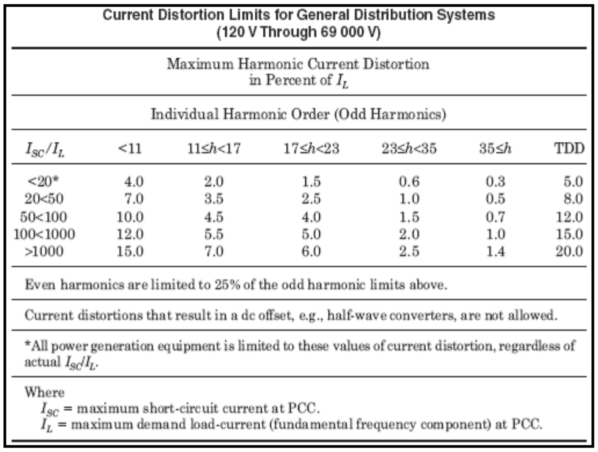

Current Distortion Limits for General Distribution Systems
(120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L

	Individual Harmonic Order (Odd Harmonics)					
I_{SC}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.

Where
I_{SC} = maximum short-circuit current at PCC.
I_L = maximum demand load-current (fundamental frequency component) at PCC.

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- With harmonics, the measuring method of the revenue meter is critical.
- Distortion can result in significantly different kVAR, kVA and power factor readings depending on the types of meters used.

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- Standard 1459 recognizes fundamental frequency billing, but proposes many other equations without clearly recommending a concise subset of preferred options for legal metrology and billing.
- Some of these other equations, could change the billing patterns of harmonic producing loads and of loads that only sink harmonics.
- How would billing be affected for revenue meters presently in use in comparison with the fundamental only method?

MEASURING METHODS FOR REVENUE METERS

- Apparent power can be based on measurements of

1) active and reactive powers

$$S_{PQ} = \sqrt{P^2 + Q^2}$$

2) sampled data of the voltage and current

$$S_{VI} = V_{rms} \times I_{rms}$$

- Power factor is the ratio of the active power to the apparent power and can be computed as

$$PF_{PQ} = \frac{P}{S_{PQ}} = \frac{P}{\sqrt{P^2 + Q^2}}$$

$$PF_{VI} = \frac{P}{S_{VI}} = \frac{P}{V_{rms} \times I_{rms}}$$

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- There are some new digital sampling meters that use the measurements of active (P) and apparent power S_{VI} to calculate reactive power as

$$Q_{VI} = \sqrt{S_{VI}^2 - P^2}$$

- Q_{VI} is extremely sensitive to an increase in S_{VI}, i.e. harmonic content of the voltage and or current waveform.

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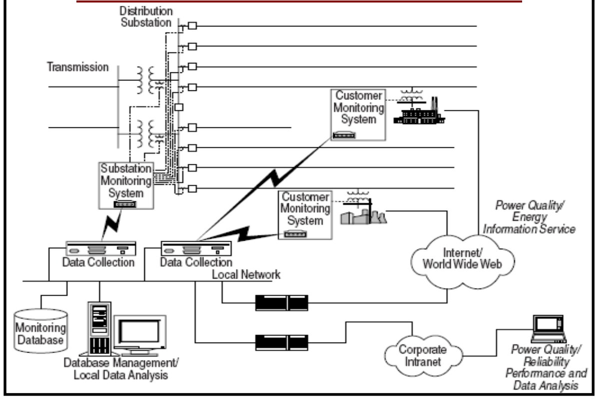
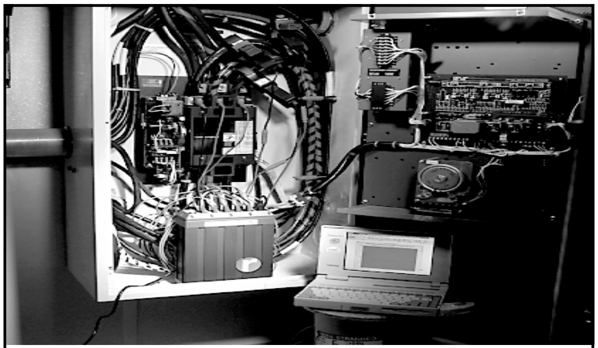
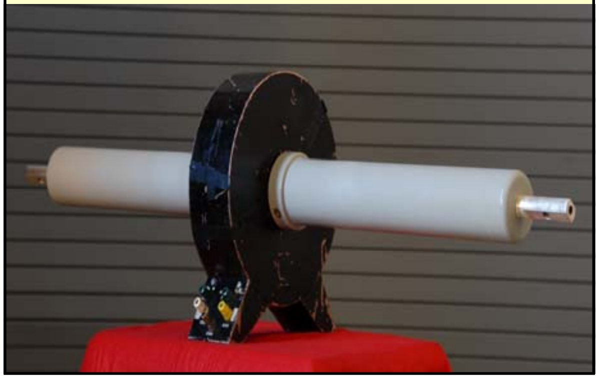
System power quality monitoring concept with monitoring at the substation and selected customer locations



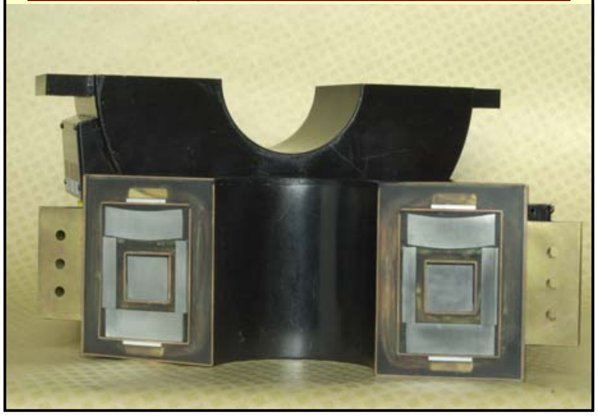


Three-phase harmonic and disturbance analyzer for measuring voltage and current harmonics, voltage and current history over a period of time, voltage transients, and power, power factor, and demand.

2000 A Two-Stage CT with 100 kV Bushing



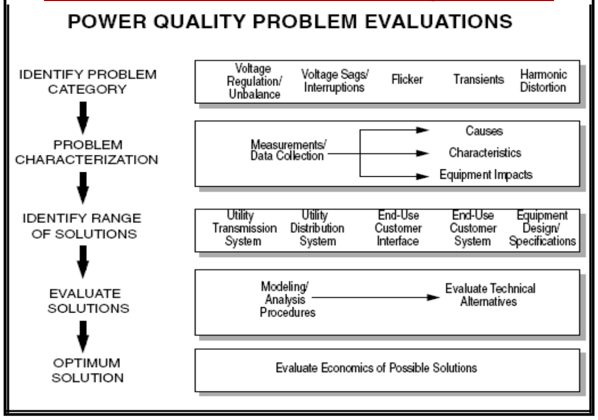
5000A/5A AC Openable-core Current Transformer



2000 A/1 A AC/DC Current Transformer

Small Current Clamp-on CT

Basic steps involved in a power quality evaluation



POWER QUALITY PROBLEM EVALUATIONS

IDENTIFY PROBLEM CATEGORY
Voltage Regulation/ Unbalance
Voltage Sags/ Interruptions
Flicker
Transients
Harmonic Distortion

PROBLEM CHARACTERIZATION
Measurements/ Data Collection
Causes
Characteristics
Equipment Impacts

IDENTIFY RANGE OF SOLUTIONS
Utility Transmission System
Utility Distribution System
End-Use Customer Interface
End-Use Customer System
Equipment Design/ Specifications

EVALUATE SOLUTIONS
Modeling/ Analysis Procedures
Evaluate Technical Alternatives

OPTIMUM SOLUTION
Evaluate Economics of Possible Solutions

Economic Impact

- Work stoppages can cost a company up to $500,000 an hour
- Power-related problems may cost companies more than $100 billion a year.
- PQ disturbances alone cost the U.S./Canada economy between 15 and 24 billion dollars annually.
- 2008 EU PQ survey concluded: The cost of wastage caused by poor PQ for EU exceeds €150bn… Industry accounts for over 90% of this wastage.

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Smart Grid

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Present Grid System

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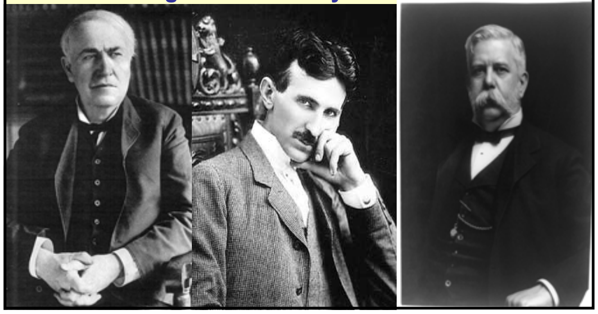
PRESENT GRID SYSTEM

Technologies and strategies that are more than 120 years old long before the proliferation of digital communications and control technologies that we rely on today.



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PRESENT GRID SYSTEM (Cont.)

- Limits systems capabilities to detect and address emerging problems before they affect services.
- The current grid system is straining under outdated technology and increasing demand for high-quality power.
- Unreliable services and blackouts, posing significant economic and safety threats to the society.

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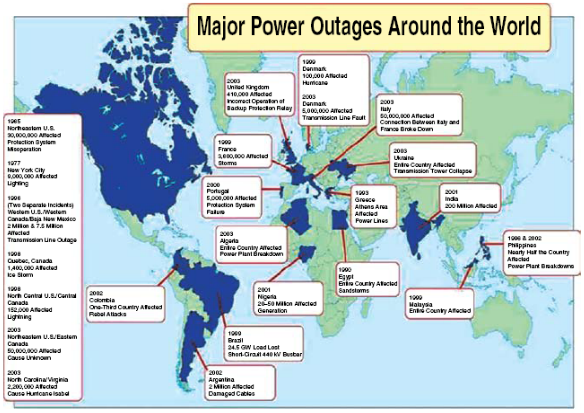
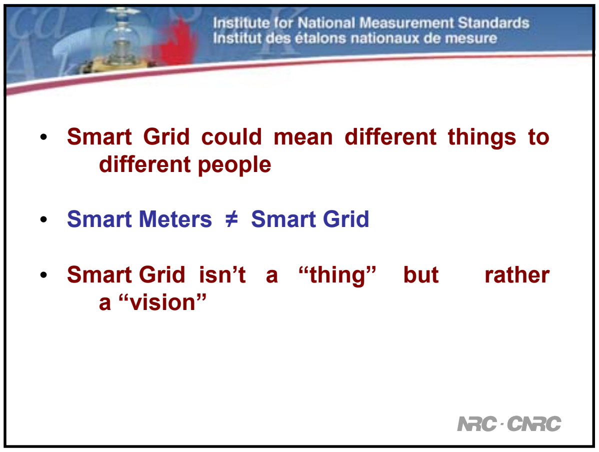


Figure 5. Electrical outages worldwide. Small-scale power outages are not shown. *Source*: EPRI PEAC Corporation; for more information on blackouts go to www.2003blackout.info (accessed January 2008).

- There are many smart grid definitions, some functional, some technological, and some benefits-oriented.
- A common element to most definitions is the application of digital processing and communications to the power grid, making data flow and information management central to the smart grid.
- Various capabilities result from the deeply integrated use of digital technology with power grids, and integration of the new grid information flows into utility processes and systems is one of the key issues in the design of smart grids.



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- Smart Grid could mean different things to different people
- Smart Meters ≠ Smart Grid
- Smart Grid isn’t a “thing” but rather a “vision”

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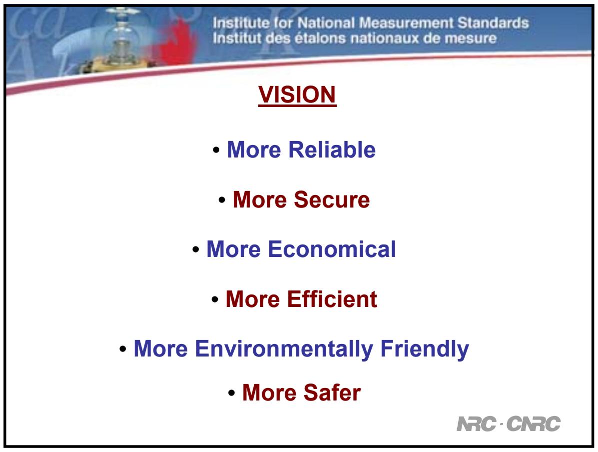

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VISION

- More Reliable
- More Secure
- More Economical
- More Efficient
- More Environmentally Friendly
- More Safer

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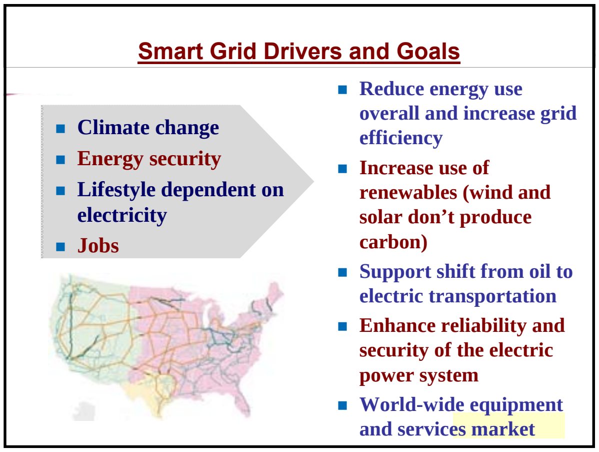
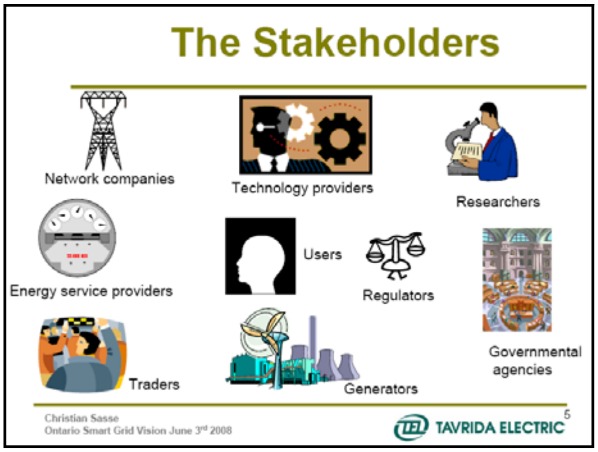


Smart Grid Drivers and Goals

- Climate change
- Energy security
- Lifestyle dependent on electricity
- Jobs

- Reduce energy use overall and increase grid efficiency
- Increase use of renewables (wind and solar don’t produce carbon)
- Support shift from oil to electric transportation
- Enhance reliability and security of the electric power system
- World-wide equipment and services market



The Stakeholders

Network companies
Technology providers
Researchers
Energy service providers
Users
Regulators
Governmental agencies
Traders
Generators

Christian Sasse
Ontario Smart Grid Vision June 3rd 2008

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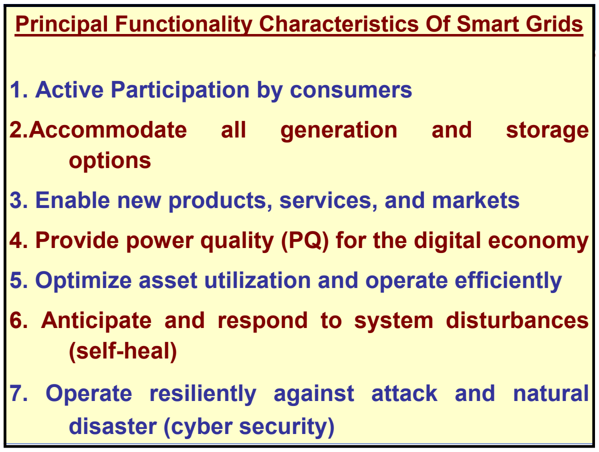
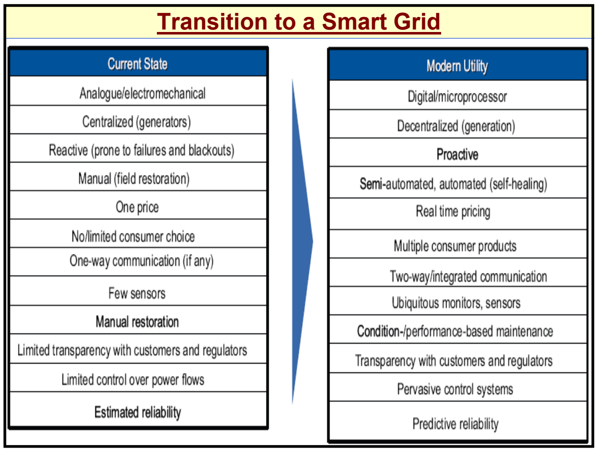
TAVRIDA ELECTRIC



Principal Functionality Characteristics Of Smart Grids

1. Active Participation by consumers
2. Accommodate all generation and storage options
3. Enable new products, services, and markets
4. Provide power quality (PQ) for the digital economy
5. Optimize asset utilization and operate efficiently
6. Anticipate and respond to system disturbances (self-heal)
7. Operate resiliently against attack and natural disaster (cyber security)



Transition to a Smart Grid

Current State	Modern Utility
Analogue/electromechanical	Digital/microprocessor
Centralized (generators)	Decentralized (generation)
Reactive (prone to failures and blackouts)	**Proactive**
Manual (field restoration)	**Semi**-automated, automated (self-healing)
One price	Real time pricing
No/limited consumer choice	Multiple consumer products
One-way communication (if any)	Two-way/integrated communication
Few sensors	Ubiquitous monitors, sensors
Manual restoration	**Condition-**/performance-based maintenance
Limited transparency with customers and regulators	Transparency with customers and regulators
Limited control over power flows	Pervasive control systems
Estimated reliability	Predictive reliability

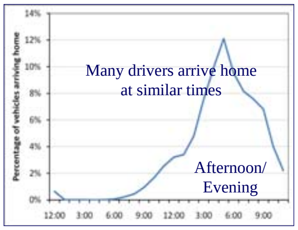
Comparison of the Current Grid and the Smart Grid

	Current Grid	Smart Grid
Communications	None or One-way	Two-way
Customer Interaction	Limited	Major
Meter Type	Electromechanical	Digital
O&M	Manual equipment checks	Remote monitoring
Power Supply Support	Centralized Generation	Centralized and Distributed Generation
Power Flow Control	Limited	Pervasive
Reliability	Prone to failures and blackouts	Adaptive protection and islanding
Restoration	Manual	Self-healing
Topology	Radial	Network

How will the Smart Grid evolve?

- High use of renewables – 20% – 35% by 2020
- Distributed generation and microgrids
- Bidirectional metering – selling local power into the grid
- Distributed storage
- Smart meters that provide near-real time usage data
- Time of use and dynamic pricing
- Ubiquitous smart appliances communicating with the grid
- Energy management systems in homes as well as commercial and industrial facilities linked to the grid
- Growing use of plug-in electric vehicles
- Networked sensors and automated controls throughout grid
- Increased cyber security into all Smart Grid functions

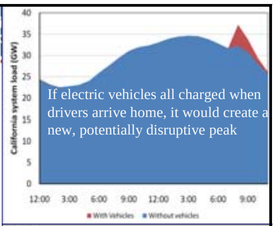
- Electric Vehicles can displace substantial oil imports, reduce CO_2 by 20%, and reduce urban air pollutants by 40%-90%
- Electric Vehicles use a significant amount of power to recharge, however



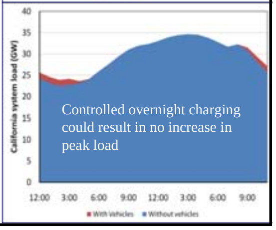
Many drivers arrive home at similar times

Afternoon/ Evening

Source: EPRI



If electric vehicles all charged when drivers arrive home, it would create a new, potentially disruptive peak



Controlled overnight charging could result in no increase in peak load

Smart Grid = Green Jobs

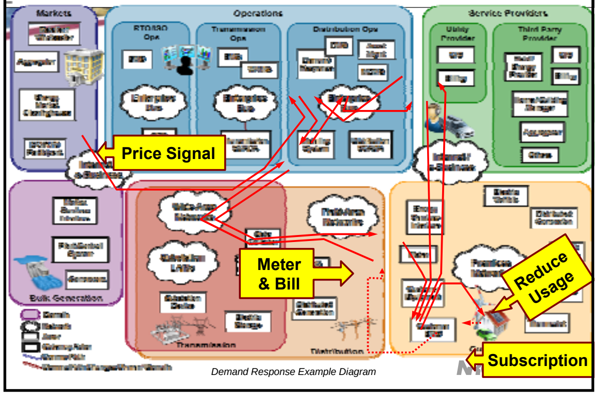
KEMA Study for Grid Wise Alliance estimates:

- 270,000 new jobs in early deployment (2009-2012)
- 170,000 new jobs in steady state (2013-2018)
- Utilities, their contractors and supply chain

Industry/Investment Priority

- Estimated $1.5 trillion investment in North America over ~20 years
  - New generation, transmission, distribution, operations, …
  - Smart Grid equipment market of $70B by 2013
  - International ecosystem of utilities, vendors, regulators, customers ($$$)
- Example: Smart Meters
  - $40 - $50 billion dollar deployment in the U.S. and Canada (Provincial Utilities)
  - Additional world-wide deployments underway and planned
  - China, U.S., EU “stimulus funding” support
  - Rapid technology evolution
  - Need to accelerate standards

Smart Grid Use Case Example: Demand Response



Demand Response Example Diagram

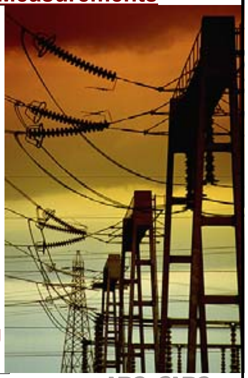
Main Important Smart Grid Sensors

- Smart Meters - Advanced Metering Infrastructure (AMI) in Distribution System (Two-Way Communication)
- Phasor Measurement Unit (PMU) in Transmission System

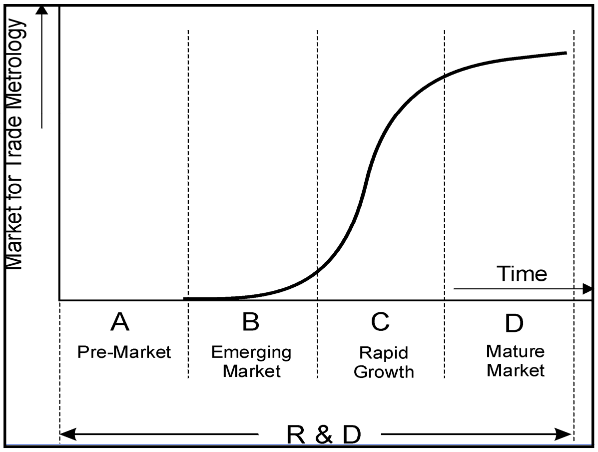
PMU – Phasor Measurement Unit

- A device that samples analog voltage and current data in synchronism with a Global Positioning System (GPS-clock).
- The samples are used to compute the corresponding phasors. Phasors are computed based on an absolute time reference (UTC), typically derived from a built in GPS receiver.
- Measured phasors at different locations can be compared if the measurements are referenced to a common time base. In this way power system dynamic phenomena can be tracked for improving power system monitoring, protection, operation and control.

Applications of Phasor Measurements



- Improved Operational Observability
- Event and System Analysis
- State Estimation
- Dynamic System Probe
- Measurement based Controls
  - Voltage controls
  - Transient angle controls
- Future Developments
  - More inter-utility data exchange
  - Adaptive Relaying (Self Healing Grid)



Conclusion

- Lots of opportunities for NMIs, Research Organizations, Regulating bodies, Standard Organizations, Manufacturers, etc. to play an important and critical role in supporting the electrical power industry in the area of Power Quality and Smart Grid, depending on the needs of the local environment/country, resources and funding.

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GRACIAS