Smart Sensors for the Smart Grid

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Sensor Tech Forum 2011

Agenda

- Overview of the Smart Grid
- Smart sensor design aspects
- Sensor networks
- Metering and power quality sensors
- Sensors for smart buildings
- Smart grid networked sensor standards
- Application areas

Overview of the Smart Grid
-- subtopics --

- What is it?
- NY ISO
- Framework
- Benefits
- Characteristics
- Architecture (3)
- Microgrid (4)
- IP Networks
- Interoperability
- Confidentiality

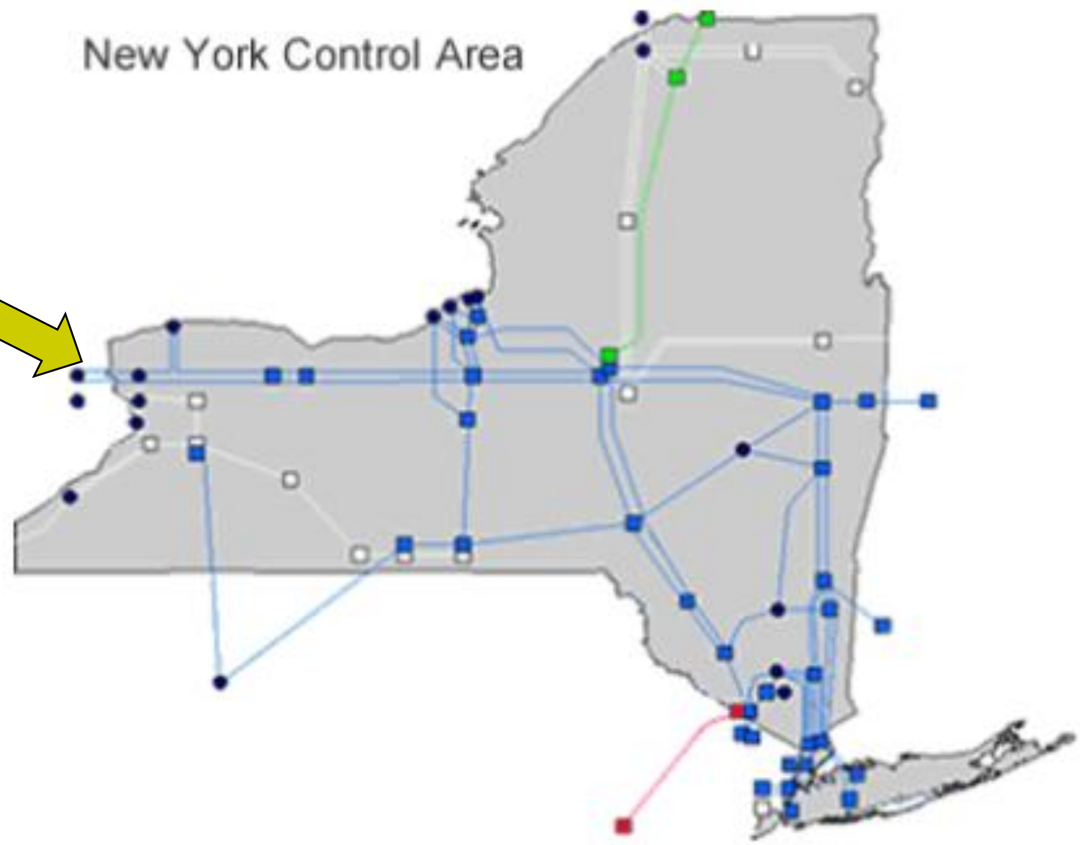
What is the Smart Grid?
(Wikipedia)

- The electrical grid upgraded by two-way digital communication for greatly enhanced monitoring and control
- Saves energy, reduces costs and increases reliability
- Involves national grid as well as local micro-grid ---
  power generation, transmission, distribution and users
- Real-time (smart) metering of consumer loads is a key feature
- Phasor network another key feature (Phasor Measurement Unit, PMU)
- Uses integrated communication (requires standards)
- Includes advanced features and control
  (e.g., energy storage, electric auto charging, solar power, DC distribution)

Electric Grid in New York

- New York Independent System Operator (NYISO)

Niagara Falls
(where it started)



SENSORS TECH FORUM

NIST Smart Grid Framework

- Report prepared by National Institute of Standards and Technology (NIST) and the Electric Power Research Institute (EPRI)
- Title: **NIST Framework and Roadmap for Smart Grid Interoperability Standards**
  [http://www.nist.gov/public_affairs/releases/smartgrid_interoperability.pdf]
- Used as reference for this presentation (Jan 2010)

Smart Grid Benefits

from Framework

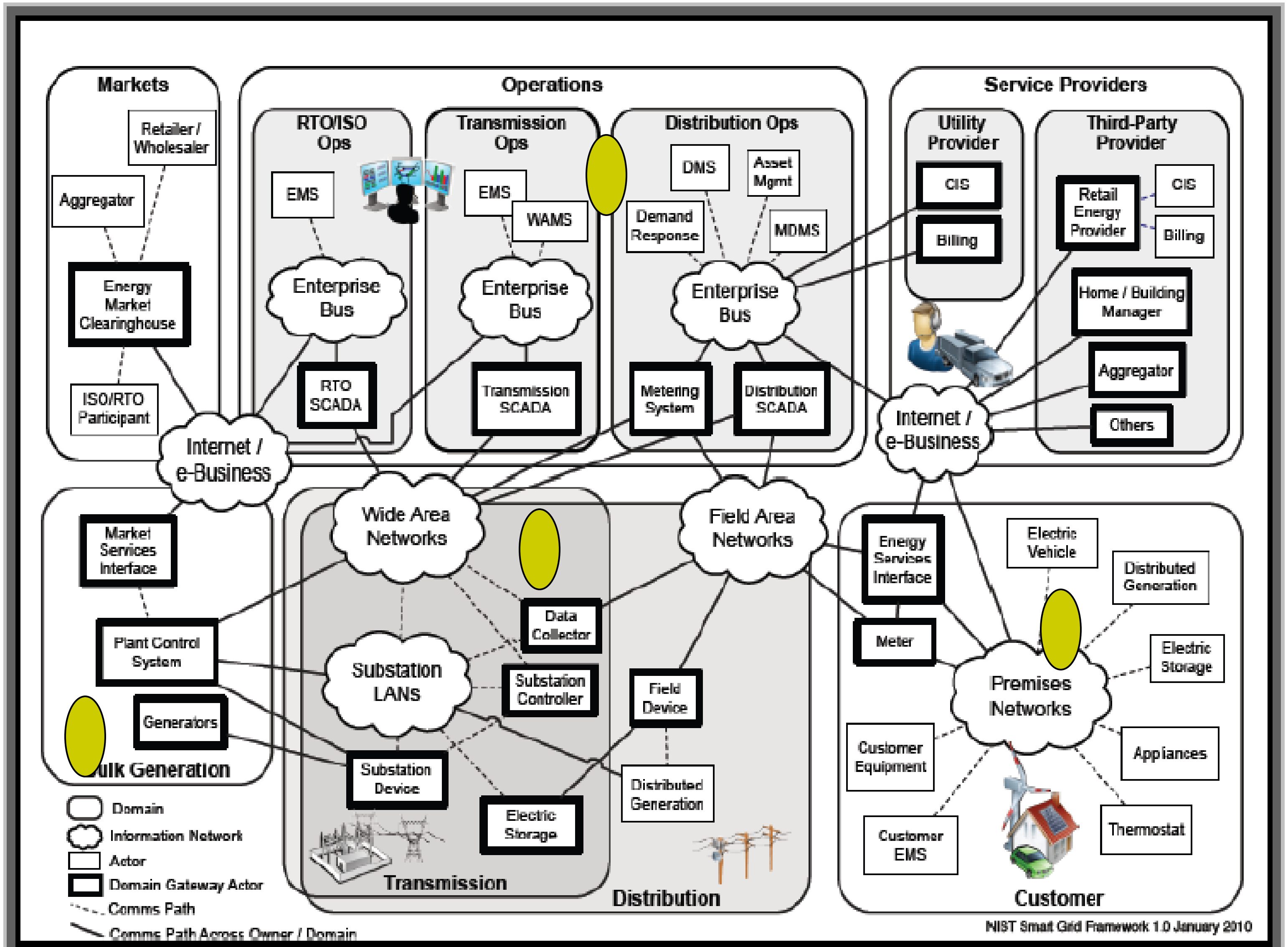
- Improves power reliability and quality
- Optimizes facility utilization and averts peak load need
- Enhances capacity and efficiency of existing electric power networks
- Improves resilience to disruption
- Enables “self-healing” responses to system disturbances
- Facilitates expanded deployment of renewable energy sources
- Accommodates distributed power sources
- Automates maintenance and operation
- Reduces greenhouse gas emissions
- Improves cyber security
- Enables plug-in electric vehicles and energy storage options

Distinguishing Characteristics
from Framework/Roadmap

- Increased use of digital information and controls technology
- Dynamic optimization of grid operations, with full cyber security
- Deployment and integration of distributed resources and generation
- Incorporation of demand response and energy-efficiency resources
- Deployment of ‘‘smart’’ technologies for metering, communications concerning grid operations and status, and distribution automation
- Integration of ‘‘smart’’ appliances and consumer devices
- Integration of electricity storage and peak-shaving technologies and electric vehicles
- Provision to consumers of timely information and control options
- Development of standards for communication and interoperability of appliances and equipment connected to the electric grid
- Lowering of barriers to adoption of Smart Grid technologies

Architecture

(NIST Roadmap)

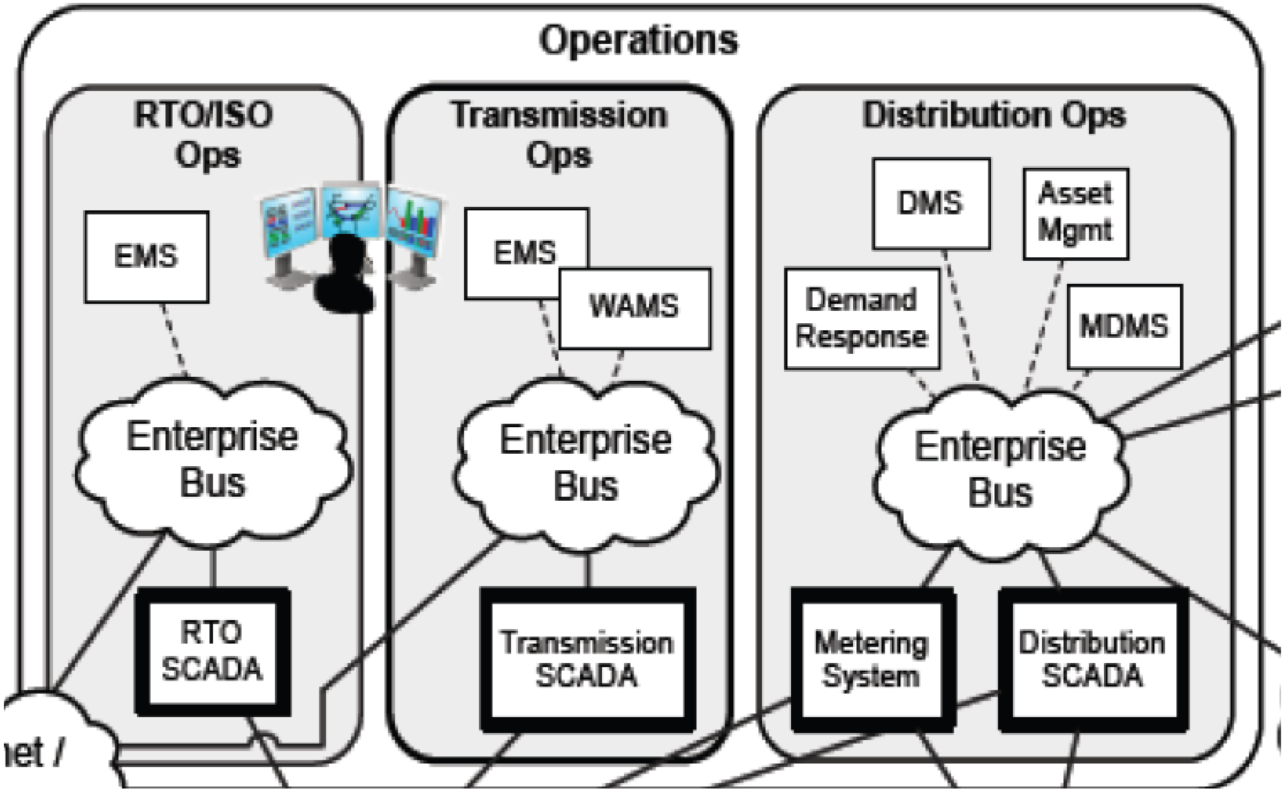


Smart Sensors & controls

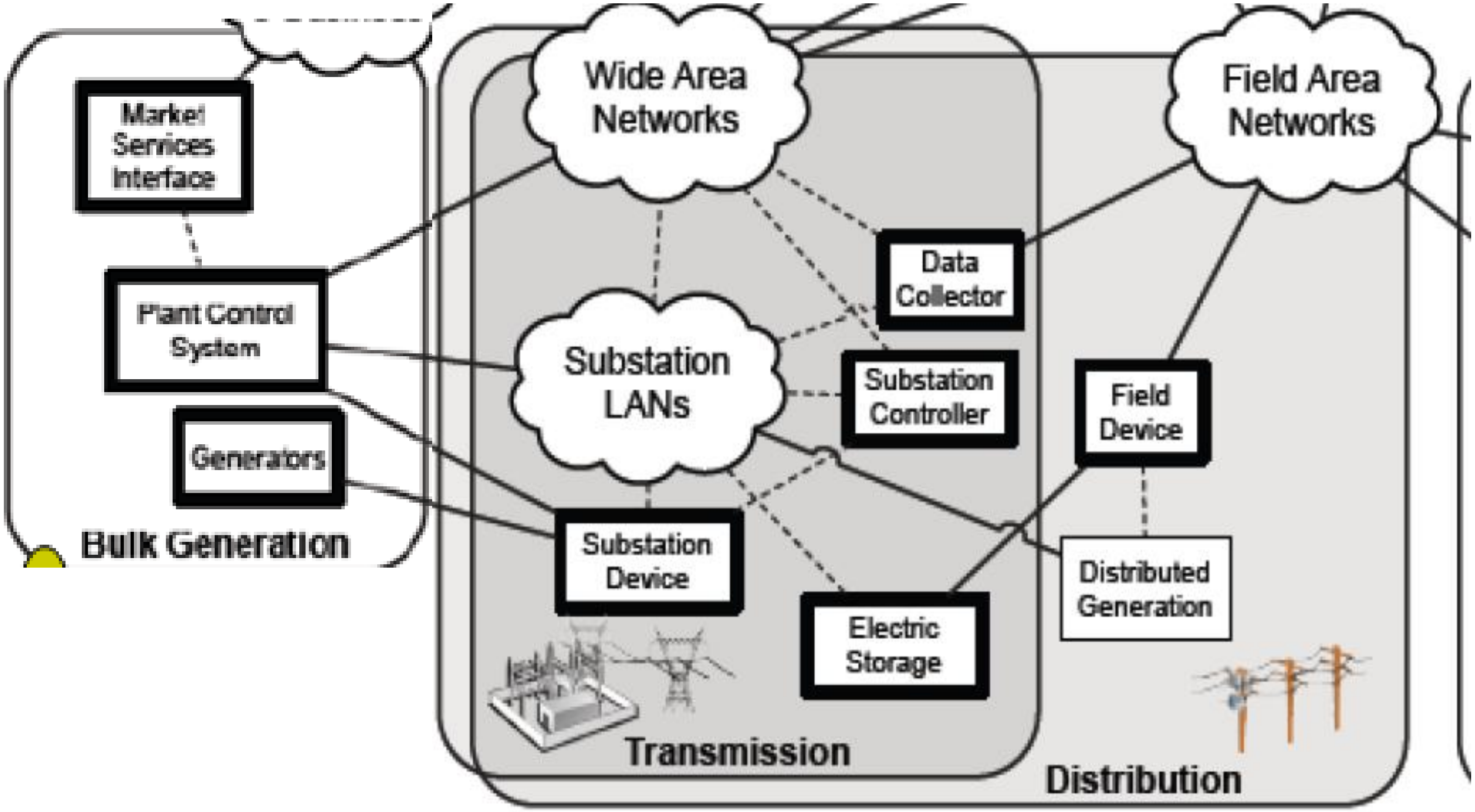
SCADA Monitoring and Control

SCADA: supervisory control and data acquisition

RTO: Regional Transmission Organization

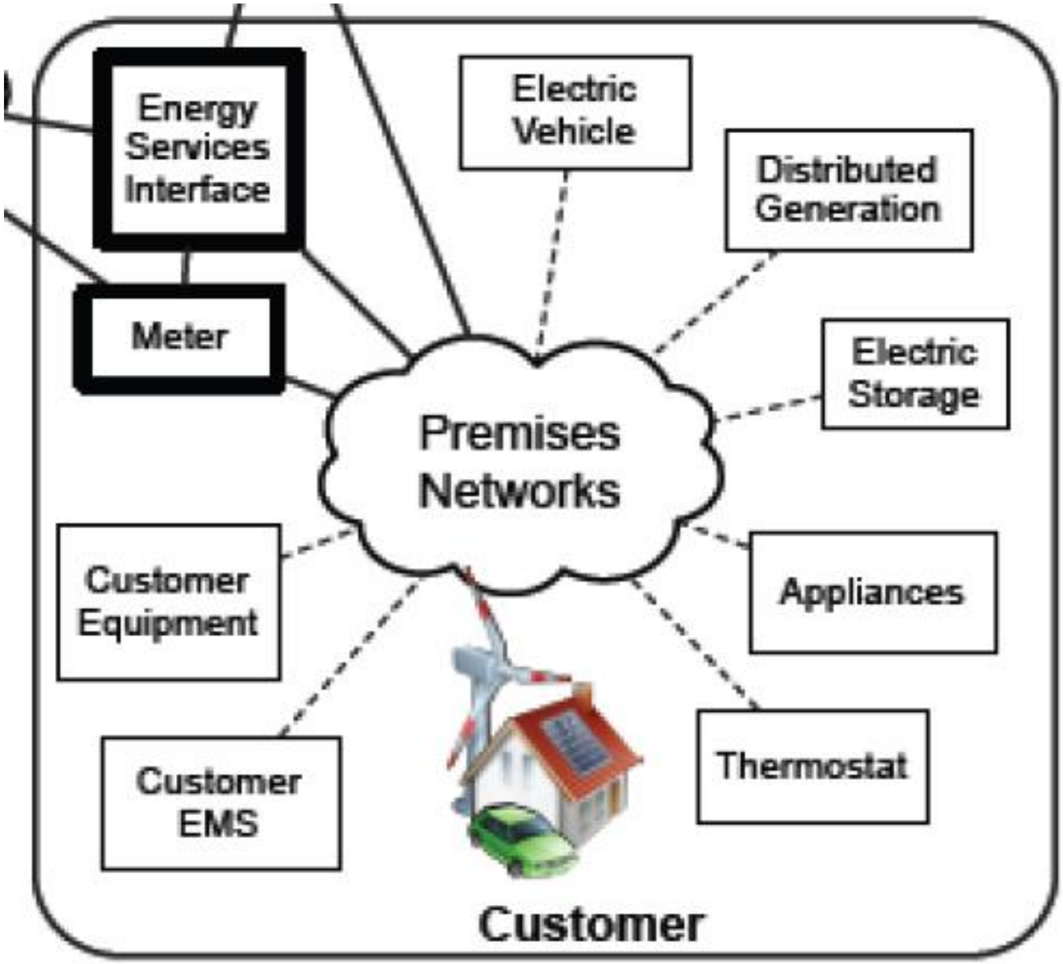


Transmission and Distribution



local Distribution and Micro-grid

A **Microgrid** is a localized group of electrical generation, energy storage and loads. It may operate independently or connected to the conventional grid.



EMS –
Energy Management
System

Sub-grid or Microgrid

- Power generation (1), transmission (2) and substations (3) are under control of Utilities
- Commercial buildings (5) and part of distribution (4) are part of local distribution or sub-grid
- All part of smart grid

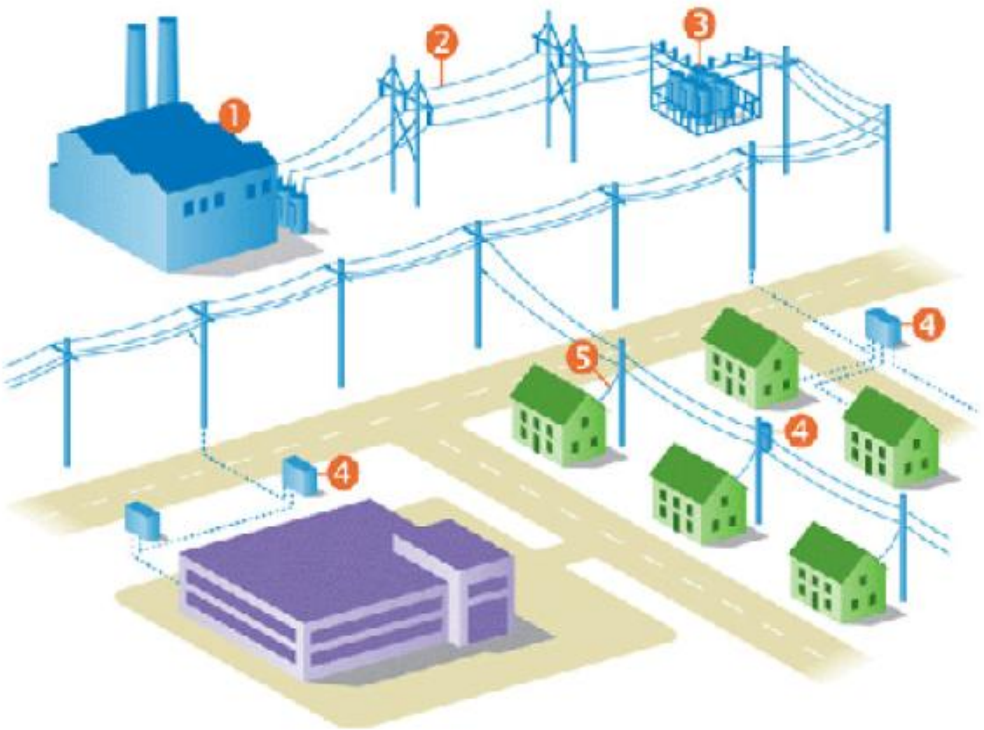


Figure --http://www.peco.com/pecores/customer_service/the_electric_system.htm

IP Based Networks

- Internet Protocol (IP) based networks are used for data communication involving the smart grid
- Acts as bridge between application and underlying sensor/control networks
- Used by both private (dedicated) and public networks
- Used also by local wireless networks

Standards and Interoperability

- TCP/IP is only the communication protocol
- Data carried as payload will be formatted by specific standards (e.g. SCADA or PMU)
- Over 75 Standards referenced in NIST Guidelines
- Sensor network standards discussed later

Confidentiality Concerns

- Data/commands requires proper level of protection
  - Data which could bring down parts of the Grid need highest level of protection
  - Encryption is needed at several levels but can be costly for small systems (more hardware, keys, permissions, etc)
  - For many local (micro-grid) applications, encryption is unneeded and counter-productive (e. g. local thermostat)
- Users need privacy protection
  - Data transfer is two-way, including at the sub-grid level with commercial business and private homes
  - Confidential information might be gleaned from smart grid data and sold to third parties
- Indirectly affects networked sensor design

Smart sensor design aspects

-- subtopics --

- Background and Sensor types (6)
- Block diagrams (3)
- Features
- Examples (3)

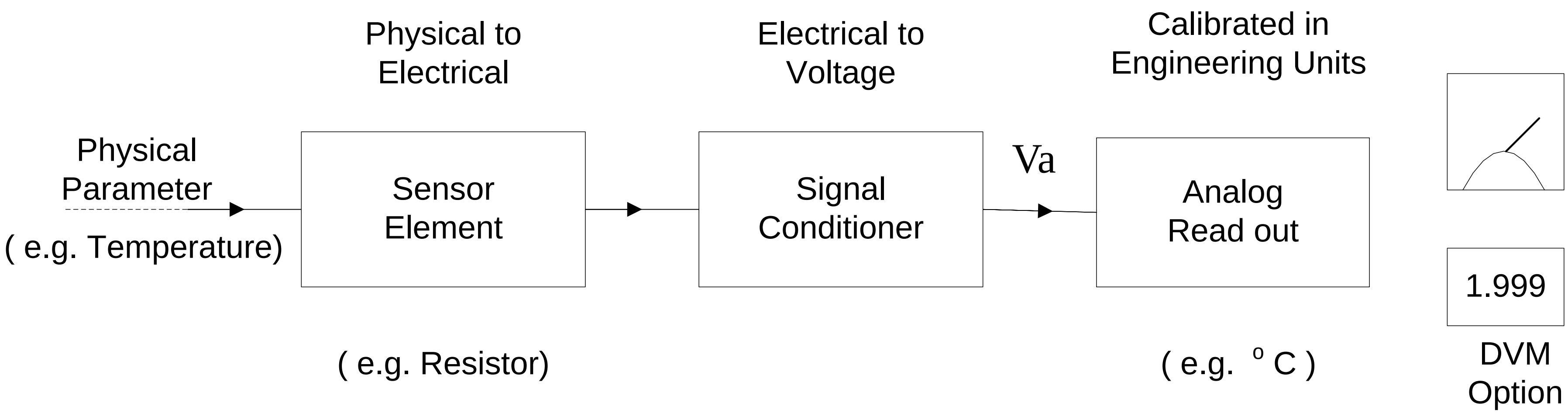
Sensor Development
past and future

- Most sensor principles known (by physicists) for over 100 years
- Many sensors used industrially for over 60 years
- Computer controls and appetite for data have driven sensor uses, especially Machine-to-Machine (M2M).
- Continuing improvements in manufacturing methods (e.g. MEMS) have made sensors smaller & easier to use
- Advances in electronics (analog, a/d, microcomputers, communications) lower costs and add functionality.
- **Smart, digital, networked sensors** are the future trend and used by the the **Smart Grid** and **Smart Buildings**

Sensor Types

- Basic Sensors
- Smart Sensors
- Networked Sensors

Basic Sensor Electronics Block Diagram



Partial List of

Measured Parameters and Sensor Technologies

- Acceleration/Vibration
- Level & Leak
- Acoustic/Ultrasound
- Machine Vision
- Chemical/Gas*
- Motion/Velocity/Displacement
- Electric/Magnetic*
- Position/Presence/Proximity
- Flow
- Pressure
- Force/Strain/Load/Torque
- Temperature*
- Humidity/Moisture*

* Used by Smart Grid

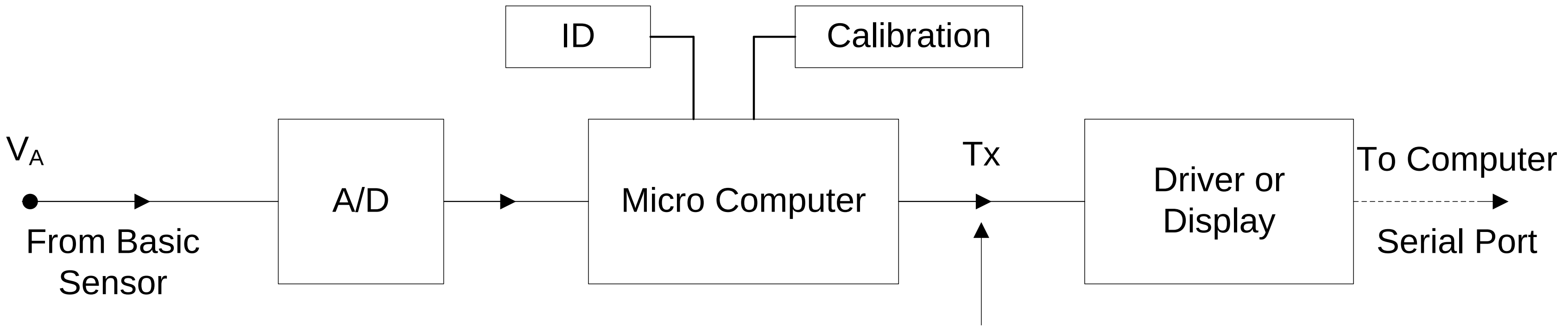
Technologies

- Resistance
- Capacitance
- Inductance & magnetics
- Optical & fiber optic
- Voltage & piezoelectric
- Ultrasonic
- RF/microwave

Sensors (and sensor industry) are subdivided (fragmented) by:

1. Parameter measured
2. Technology
3. Application area

Smart Sensor Block Diagram



Smart (Digital) Sensor Features

- Analog/Digital Converter
  - Typically 10-14 bits, usually internal
- Microcontroller (embedded)
  - PIC or similar 8-bit (or 16-bit) micro with appropriate features
- Sensor Identification (serial # etc)
- Calibration information
  - Compensation for sensor variations; conversion to engineering units
- Data logging and real-time clock (optional)

Microcontroller Example

Pin Diagram

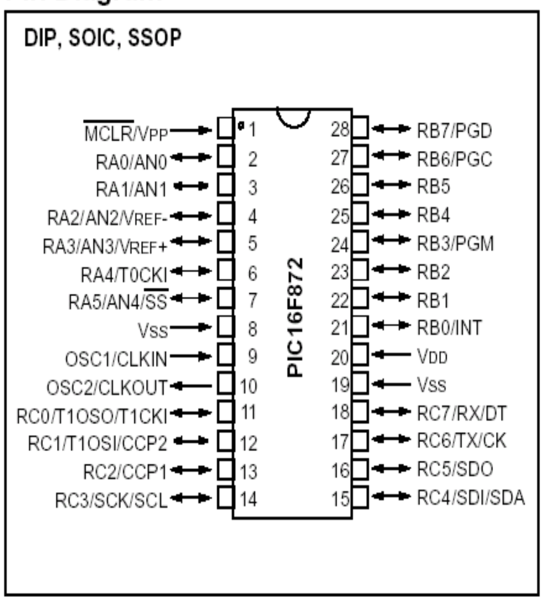
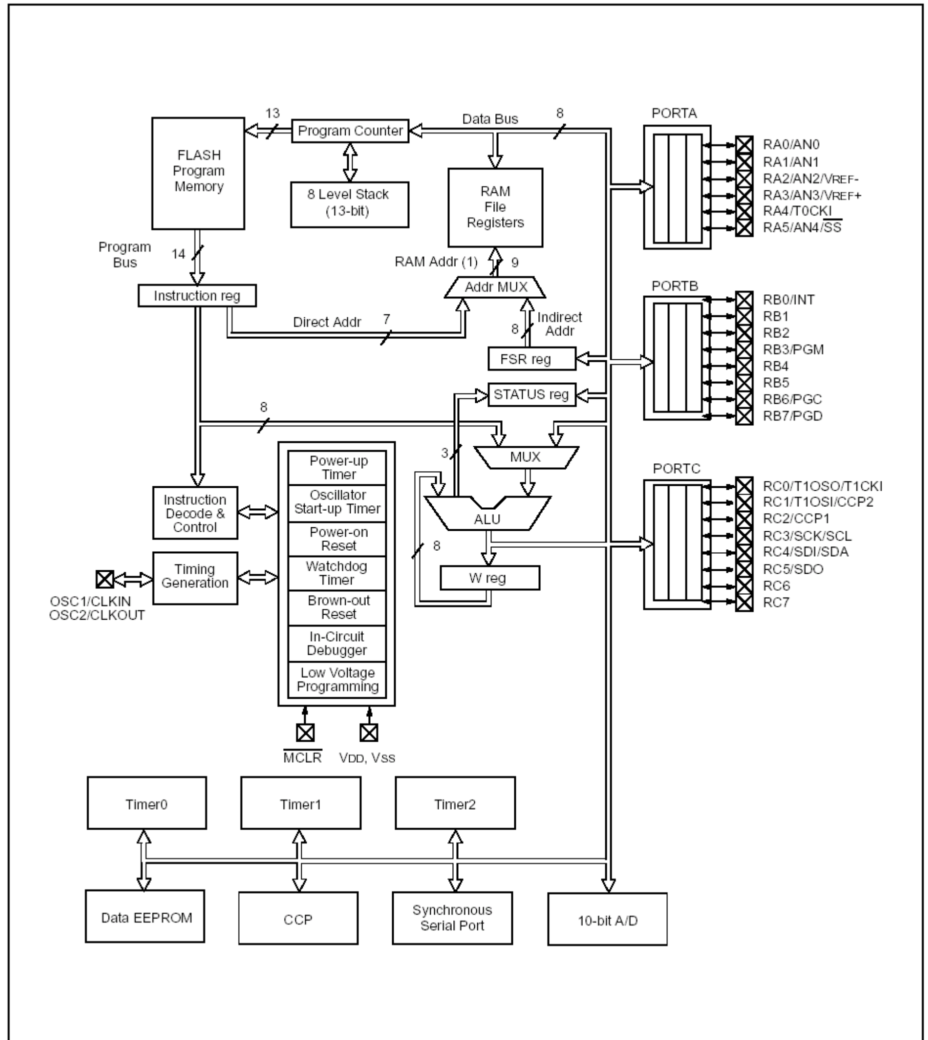


FIGURE 1-1: PIC16F872 BLOCK DIAGRAM



Note 1: Higher order bits are from the STATUS register.

Connection of Non-networked Smart Sensors to Computers

- Serial Data Lines: USB (best for PCs) or RS232 (best for Instruments)
- One line and port per sensor (a problem with large systems)
- Data is digital but format is often not standardized

Example of Sensors with Internet Address

- Uses Ethernet or WiFi as the Network
- Microcontroller has TCP/IP (mini-website) as protocol
- Data can be read anywhere on Internet
- Websensor Polling/display by NAGIOS (Linux) open source
- A smart sensor but does not have standard interface

Websensor

Sensor Networks

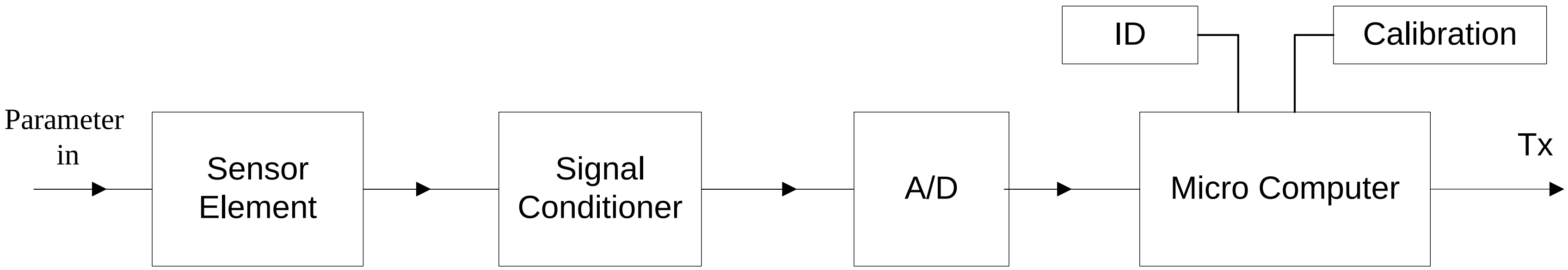
-- subtopics --

- Electronics block diagram
- Multi-level Data Protocols
- Transducer networks
- Serial bus examples
- Wireless sensors
- Data readout example

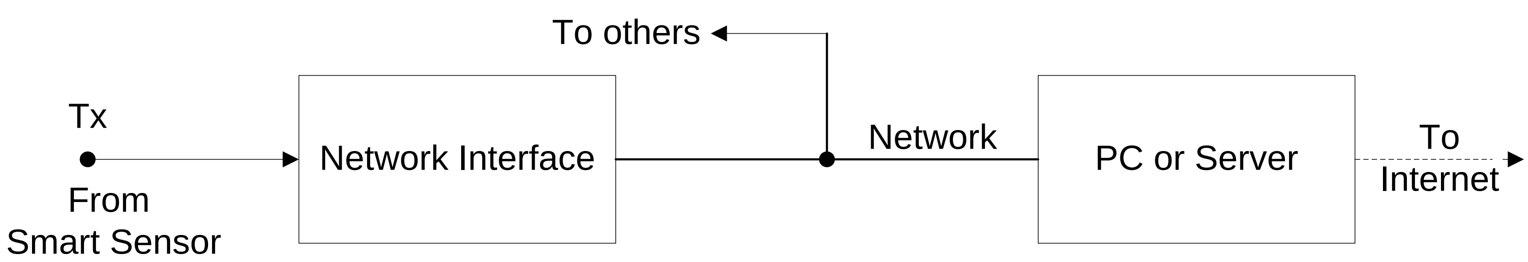
[Standards discussed later]

Networked Sensor Block Diagram

(local network or bus)



SMART SENSOR



Multi-level Data Protocols

- Data formats: How commands and transducer data are encoded (e.g. units, data type). Must be standard format for machine readability (M-to-M).
- Communication formats: How digital data is transmitted over network (e. g. IEEE 802.15.2g WiFi). Associated with physical (hardware) layer.
- Multi-level often has encapsulated data of form:

  Header(*Subheader*{data}*subfooter*)footer
- On Internet TCP/IP data often uses XML format
- Local sensor network standards sometimes combine data and communication formats

Serial Bus Examples

- RS232 or UART
- RS485 (multi-drop)
- USB
- SPI or I2C

Wireless Sensors

(Uses RF transceivers for short-range in unlicensed band)

- Significant power available
  - Line-powered or laptop sized battery
  - E.g. WiFi (IEEE 802.11b) 2.4 GHz)
  - Variation of TCP/IP protocol, mostly non-standard
- Medium low power
  - Re-chargeable batteries or shorter life applications
  - E.g. Bluetooth (IEEE 802.15.1)
- Very low power (long life operation -years)
  - Batteries or energy harvesting
  - Low bandwidth, sleep mode
  - E.g. Zigbee (IEEE 802.11.5) – mesh
  - *More information in later slide*

Metering and Power Quality Sensors

-- subtopics --

- Electrical Measurement
- Metering types
- Voltage Measurements
- Current Measurements
- Power measurements
- Frequency and Phase

Electrical Measurement Sensors

- Basic Parameters Measured
  - Voltage
  - Current
  - Time
- Derived parameters
  - True power and RMS values – averaged over cycle
  - Apparent power, power factor and VAR*
  - Accumulated energy (watt-hours)
  - Minimum and peak (e.g. voltage sag)
  - Harmonics, sub-harmonics and flicker
  - Phase and frequency

*Volts-Ampere Reactive (power)

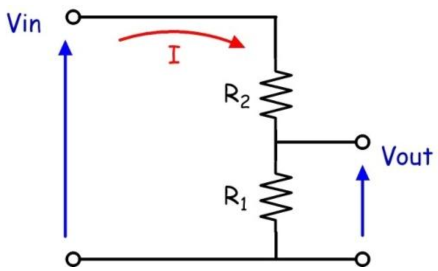
Metering types

- Power Quality
  - Measures all electrical parameters accurately (voltage, current, power, harmonics, phase)
  - Needed at substations and power distribution points
  - If updated each cycle, high bandwidth required
- Metering
  - Accurate (0.2%) measurement of true power (for revenue)
  - Energy (w-hr) calculated, often by time slots
  - Standard: ANSI C12
- Load monitoring
  - Low-cost, less accurate meters for point-of-load status
  - Voltage and current, but maybe not true power

Voltage Measurements

- Resistive Voltage Divider (N:1)

  Vin over 100 v, Vout under 1 v



- Potential Transformer (V:120v)

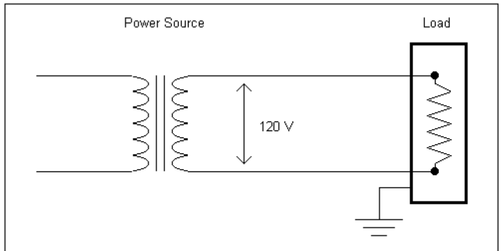
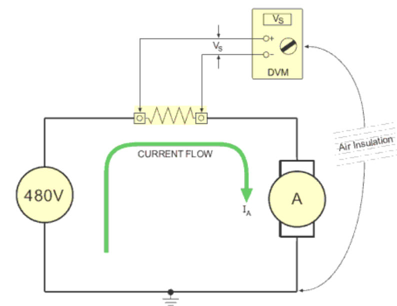
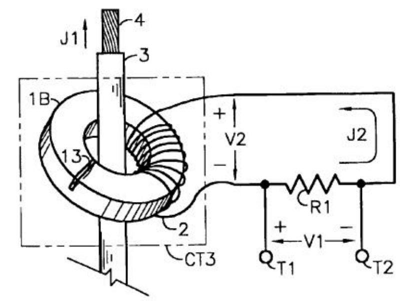


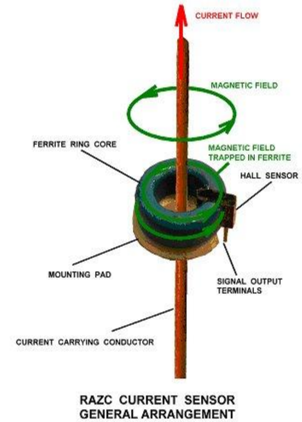
Fig. 3 120V. 60Hz power applied to a load in Transverse Mode.

Current Measurements

- Resistive Shunt
  - Typically lower currents (< 20 amp)
  - $V = R_S * I$
  - Not isolated line
- Current Transformer (CT)
  - Typically mid to high currents
  - Current reduced N:1
  - Isolated -Low R load (maybe internal)
  - Inductive coil option (low-cost)
- Hall Sensor
  - Based on Hall Effect (V = k * I)
  - Excellent high frequency response (also DC)
  - Isolated

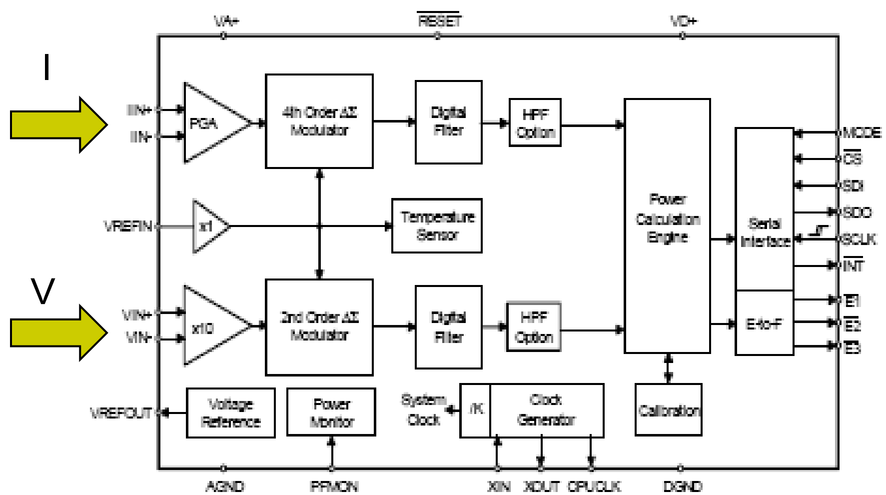




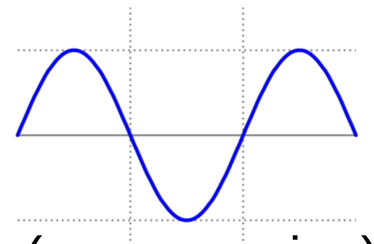


Power measurements

- True power (P_{true}) is average of P(t) = V(t)*I(t) over a cycle
  - Metering (revenue) always uses true power
- Apparent power (P_{apr}) = V_{rms} * I_{rms}
  - Greater than true power if load is partly reactive (e.g. motor)
- Power factor (cos θ) = P_{true}/P_{apr}
  - Less than 1.00 for non-resistive loads
- Precision of 0.1% requires 14-bit a/d or better
- True power meter chips available (e.g. CS5463)
- Often three phase needed

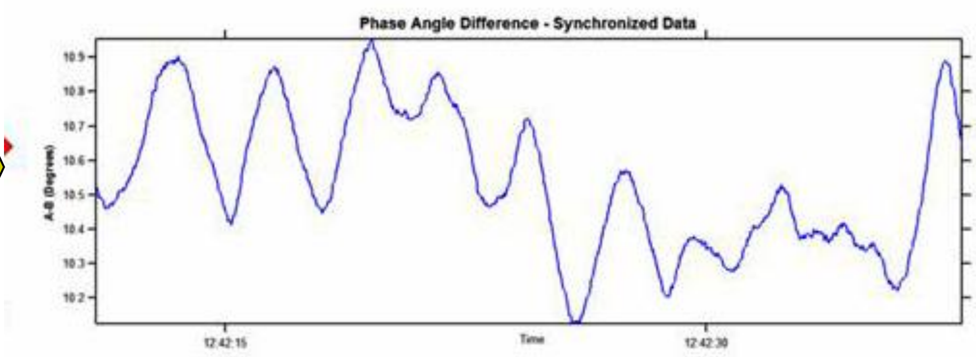


Frequency (f) and Phase (θ)



- Time derivative relationship: F = dθ/dt
- Phase measurements use phase locked loops (zero crossing)
- Time accurate to 1 µs (GPS) preferred
- Phasor Grid Dynamics Analyzer™ (PGDA) v 1.0
- Phase resolution of 0.01 º *(below -- plot steps of 0.1 º)*
- Frequency resolution to 0.001 Hz

Range
10.1 to 10.6 deg



Non-Electrical Smart Grid Sensors
-- subtopics --

- Smart Building Concept
- HVAC
- Energy Conservation
- Substation/ Transmission

Smart Building Concept

- Integration of HVAC, fire, security and other building services
- Reduce energy use
- Automation of operations
- Interaction with outside service providers (e.g. utilities)
- Three main wired standards:
  - BACnet, Lonworks and Modbus
- Three wireless standards:
  - WiFi , Zigbee, Z-wave
- Two smart building organizations
  - ASRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers)
  - Remote Site & Equipment Management

HVAC Sensors
(Heating, Ventilation and Air Conditioning)

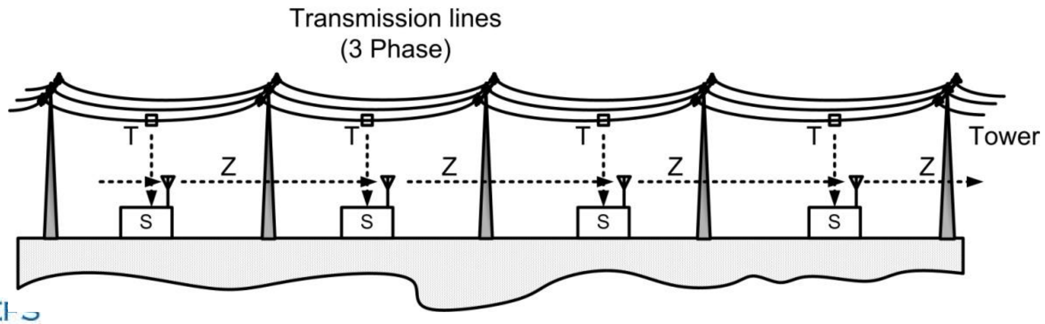
- Temperature
- Humidity
- Air Flow
- Air quality (gases: CO_2, CO, VOC)
- Also Actuators (control of heating, ventilation, AC)

Energy Conservation Sensors

- Temperature
- Illumination
- Occupancy sensors
- Wireless room controls (e.g. lighting)
- Remote access (Smart grid, Internet)

Substation/ Transmission Sensors

- Substation Equipment monitoring
  - Temperature
  - Transformer oil moisture
  - Breaker SO_2 in SF_6
- Weather
- Transmission Line Sag



Time Synchronization

-- subtopics --

- Precision
- GPS time
- Via Ethernet [IEEE 1588] (2)
- Via Wireless

Clock Precision needed

For measurement of :

Phase (at critical sites)	1 µs
Sensor synchronization (some)	1 ms
Loads (most)	1 sec

Needs vary widely

GPS Time Clock

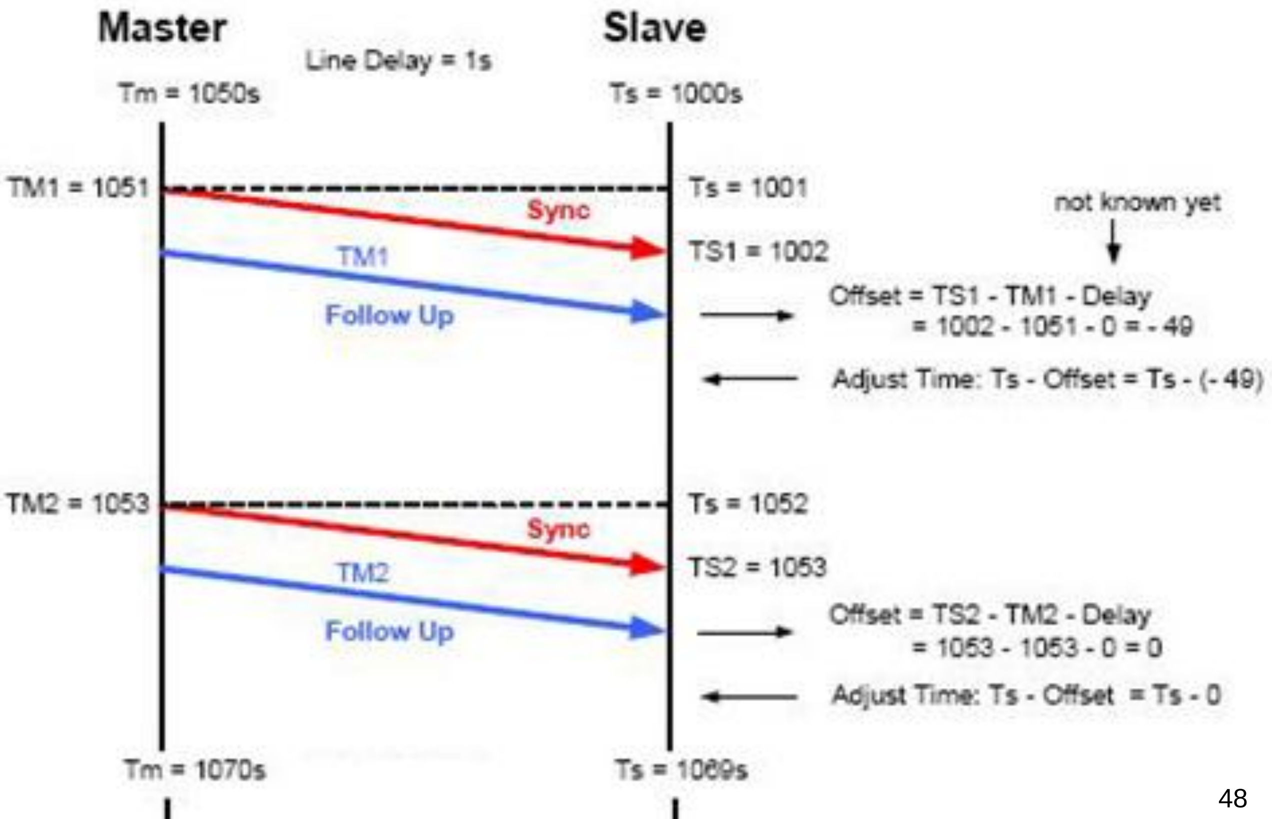
- Derived from Global Positioning System (NAVSTAR)
- Accurate time (from NIST) within 0.5 µs (non-mobile installations)
- Precision clock instruments available for multiple vendors
- Normally used at generating stations and key distribution points on Grid

Via Ethernet (Internet)

- Time in μs available from NIST via Internet in several formats (widely used). --Accuracy typically 0.1 sec
- For local synchronization a master clock on one Ethernet node is used which is synchronized to other nodes via IEEE 1588 Precision Clock Synchronization Protocol
  - Relative precision typically 0.05 μs between local nodes
- NTP format -- 64-bit timestamp containing the time in UTC sec since EPOCH (Jan 1, 1900), resolved to 0.2 μs
  - Upper 32 bits: number of seconds since EPOCH
  - Lower 32 bits: binary fraction of second
- Real time clock backup – typically 0.01 sec

IEEE 1588 Protocol

- Transmission delay time measured and compensated



Smart Grid Sensor Network Standards

-- subtopics --

- Smart Grid Standards Examples (2)
- SCADA and PMU
- Building control
- Industrial control
- Transducer Data Standard [IEEE 1451] (5)

Standards Examples*
(from NIST Framework)

4 DNP3 - This standard is used for substation and feeder device automation as well as for communications between control centers and substations.

8 IEEE C37.118 - Synchrophasor Protocol (synchrophasor):

This standard defines phasor measurement unit (PMU) performance specifications and communications.

9 IEEE 1547 Suite - This family of standards defines physical and electrical interconnections between utility and distributed generation (DG) and storage. [http://grouper.ieee.org/groups/scc21/dr_shared/]

19 IEEE P2030 Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with Electric Power System (EPS) and End-Use Applications and Loads.

- Standards, guidelines to be developed by IEEE P2030 Smart Grid Interoperability.

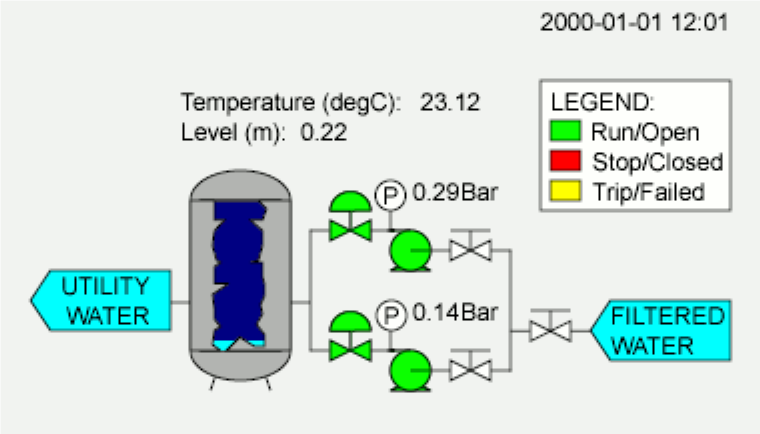
23 IEEE C37.2-2008 - IEEE Standard Electric Power System Device Function Numbers - Protective circuit device modeling numbering scheme for various switchgear.

*D. Hopkins "Smart Grid" Webinar

50

SCADA and PMU Standards

- **Supervisory Control and Data Acquisition** is current control system which has these parts:
  - Human-Machine Interface (HMI)
  - Remote Terminal Units (RTUs) – converts sensor signals to digital data (alternative: Programmable Logic Controller)
  - Communication infrastructure connects to the supervisory system
- Uses Modbus and other sensor networks (also TCP/IP extensions)
- Phasor Measurement Unit protocol uses cycle by cycle phase measurements plus SCADA and other information via dedicated network

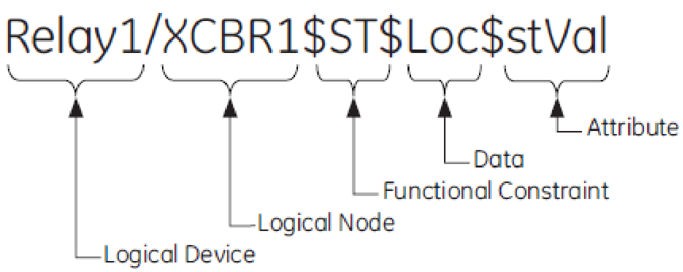


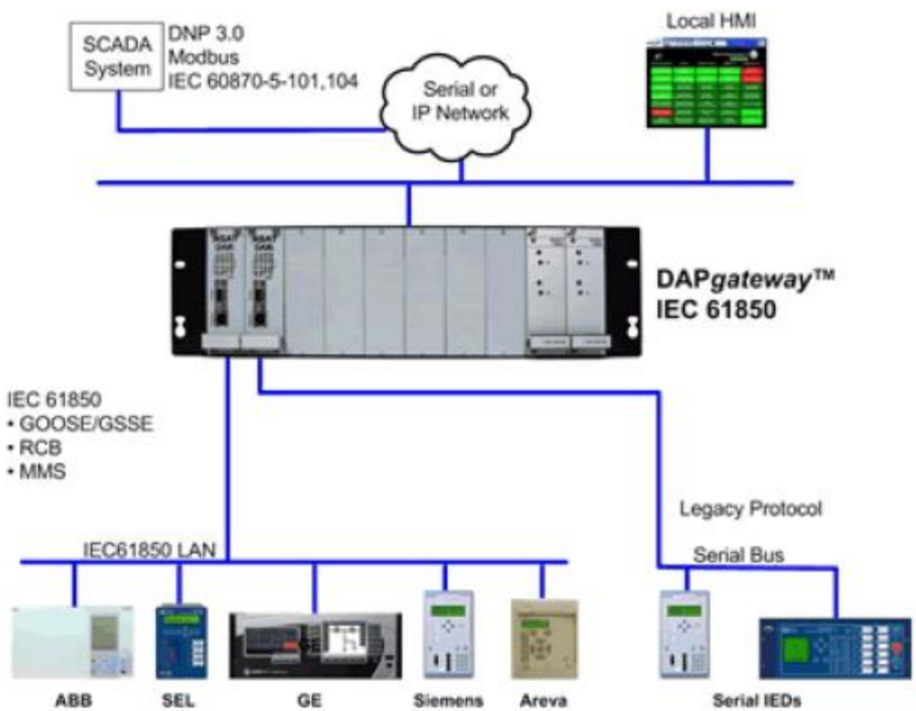
Human-Machine Interface

(from Wikipedia)

Substation Network Standard (IEC 61850)

- Communication networks and systems in substations
- Migration from the analog world to the digital world for substations
- Multi-vendor interoperability -- vendor protocol of choice





Not directly involved with sensors

http://seclab.web.cs.illinois.edu/wp-content/uploads/2011/03/iec61850-intro.pdf

Building Control
(HVAC, lighting)

- Modbus (RS232/serial originally)
- BACnet - building automation and controls network (originally RS485)
- LonWorks (2-wire proprietary)
- All have TCP/IP (Ethernet) extensions, now commonly used
- Wireless versions (WiFi, Zigbee,6LoWPAN)
- Some command examples (BACnet)
  - Read Property
  - Write Property
  - Device Communication Control
  - ReinitializeDevice
  - Time Synchronization

Industrial Control Networks and Busses

- Over 100 networks in use
- Industrial Ethernet popular for base communication
- Older, still used alternatives: RS232/RS485
- Popular Digital Buses
  - HART (over 4/20 ma loop)
  - Profibus/fieldbus
  - OpenCAN/DeviceNet
- Wireless HART/ISA 100

Network Sensor Applications

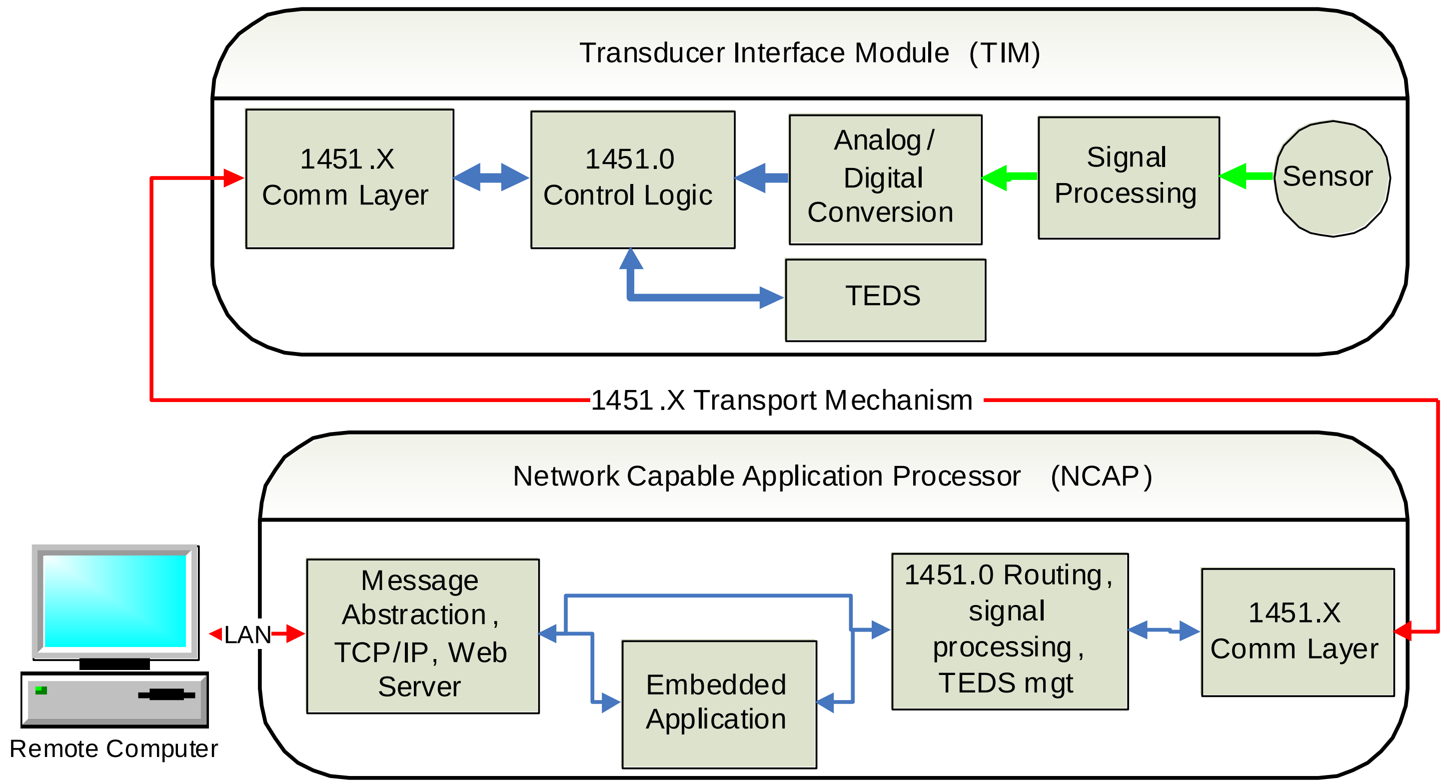
- Automatic testing
- Plug and play
- Multiple sensors on one network or bus
- Machine to Machine (M2M) sensor data communications
- Wide area (Nationwide) data collection ability

IEEE 1451 – the Universal Transducer Language

- Problem: too many network protocols in common use
  - Narrow solutions and borrowed protocols have not worked
  - Sensor engineers in the fragmented sensor industry need a simple method of implementation

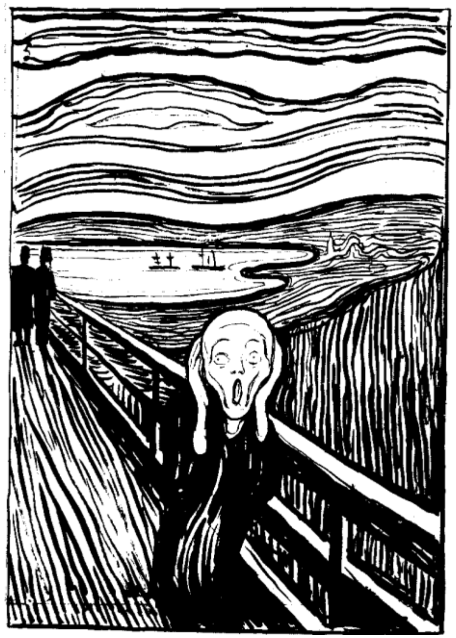
- *How can it be done*?
  - We need something like USB, except for sensors
  - Solution: the IEEE 1451 Smart Transducer Protocol open standard is the best universal solution
  - Supported by NIST, IEEE and many Federal agencies

A review of the
IEEE 1451 Smart Transducer Concept



But the Complexity!

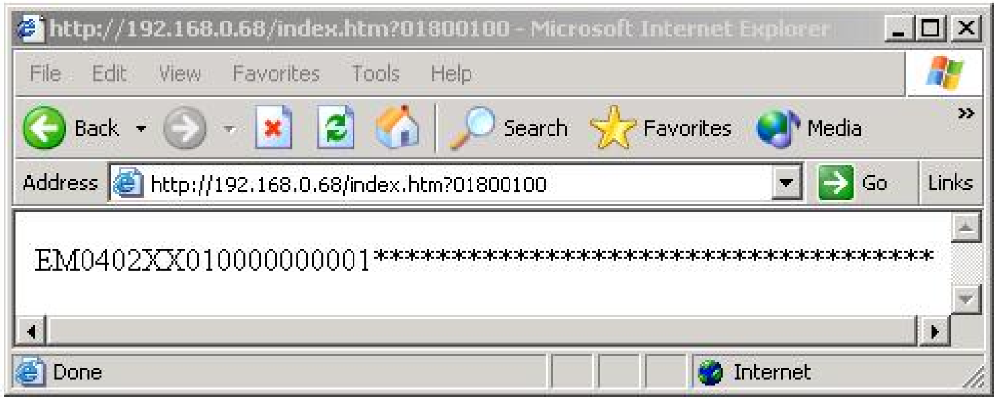
- A comprehensive standard is necessarily complex
- There was little adoption of the original IEEE 1451.2 (TII) standard because of its perceived complexity
- Manual preparation of the TEDS is not practical -- A TEDS compiler is needed
- A compliance test procedure is also desirable to prove that a design is correct



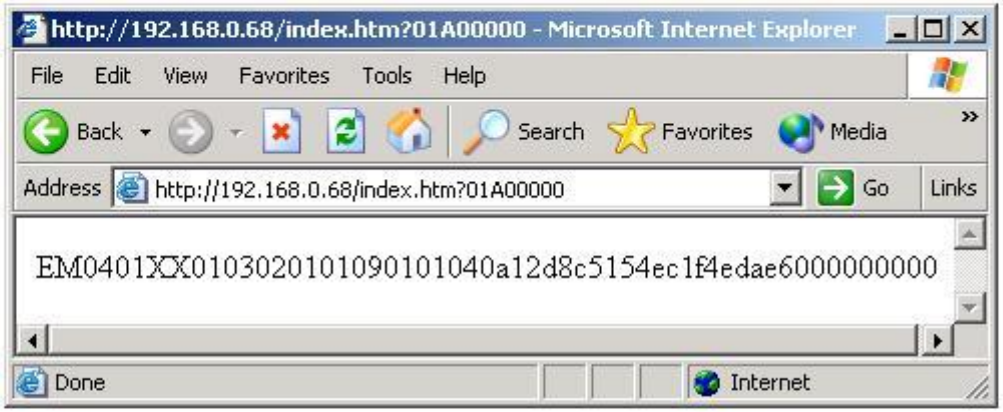
Munch –The scream

Data Readout Examples
(via Internet)

- Sensor data converted to ASCII for display



- TEDS data is displayed in hexadecimal form



Serial Bus Format
and Relation to other Networks

- Tester uses RS232 serial bus only but…
- Interfaces to other physical devices (USB, RS485, Bluetooth, Zigbee, ….) available.
- TEDS retrieval is one feature
- Sensor data read (protocol check) for each channel:

  Idle mode – full scale value of sensor reading

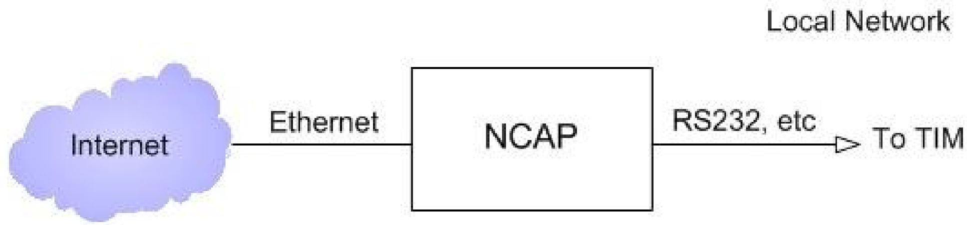
  (Checked against TEDS, error flag is not correct)

  Operating mode – actual sensor reading

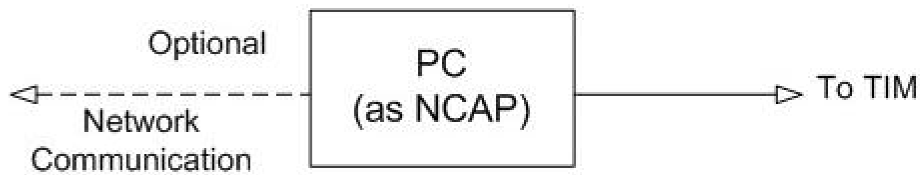
  (Must be within sensor range)

Network side (NCAP) options
(wired)

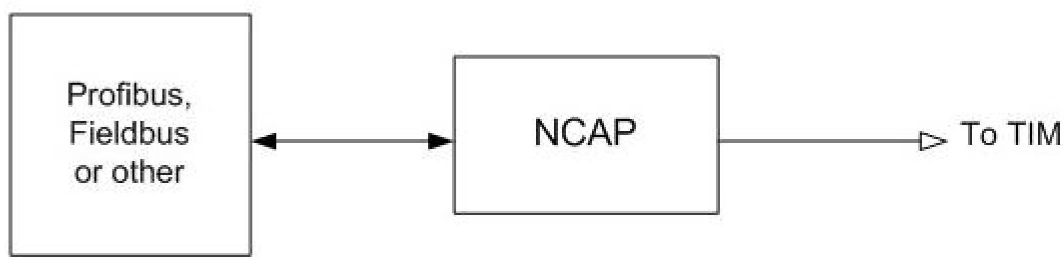
- Internet/Ethernet



- PC Readout



- Industrial network



All use Dot 0 protocol

Discussion of Network Standards

- Smart Grid Standards Examples
- SCADA and PMU
- Building control
- Industrial control
- Transducer Data Standard [IEEE 1451]

Some Application Areas for Smart Grid

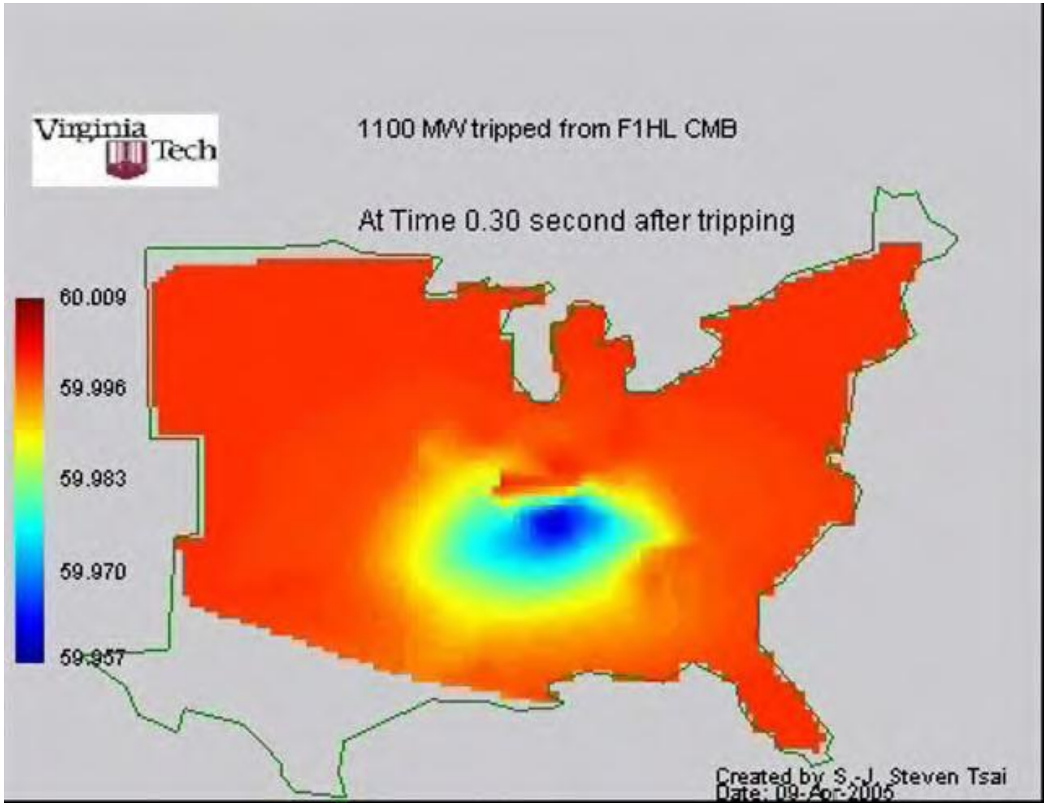
-- subtopics --

- Blackout avoidance (3)
- Smart metering
- Demand/ Response
- Energy Conservation (2)

Frequency shift and blackout

- Shifts preceding blackout (ref: SERTS report -- 2006) http://phasor-rtdms.com/downloads/presentations/DOE_Briefing.pdf
- -0.06 Hz near fault area
- Identifies trouble spots for response
- Fast reaction needed
- Phase relation:

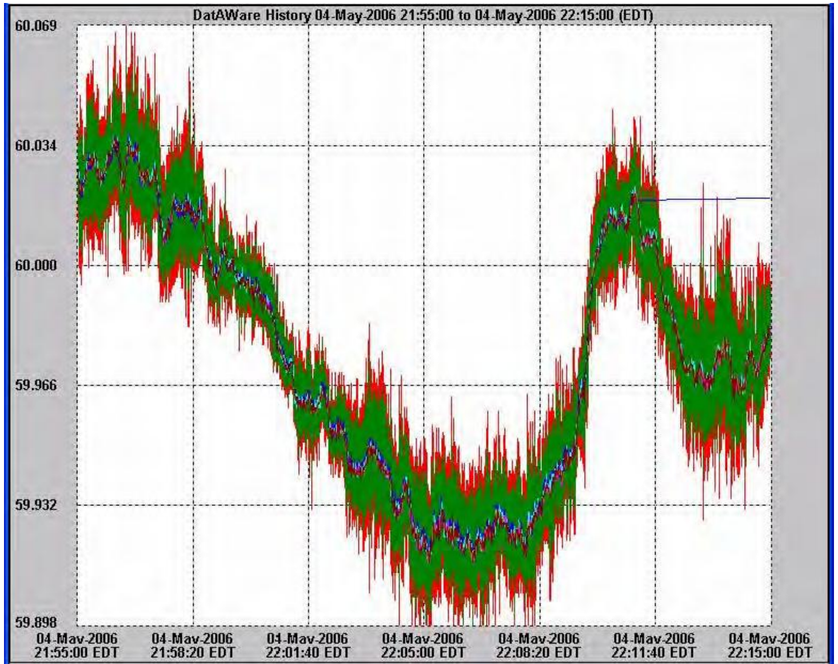
$$F = d\theta/dt$$



Abnormal frequency variations over time

- Large variations are a pre-backout warning
- A cause for concern already in June 2006 ---
  60.07 to 59.90 Hz. in plot below
- Relaxing precise control to 60 Hz is under consideration
  (slightly longer term drifts allowed – relaxes need for instant energy)

60.000 Hz



Measurement Points

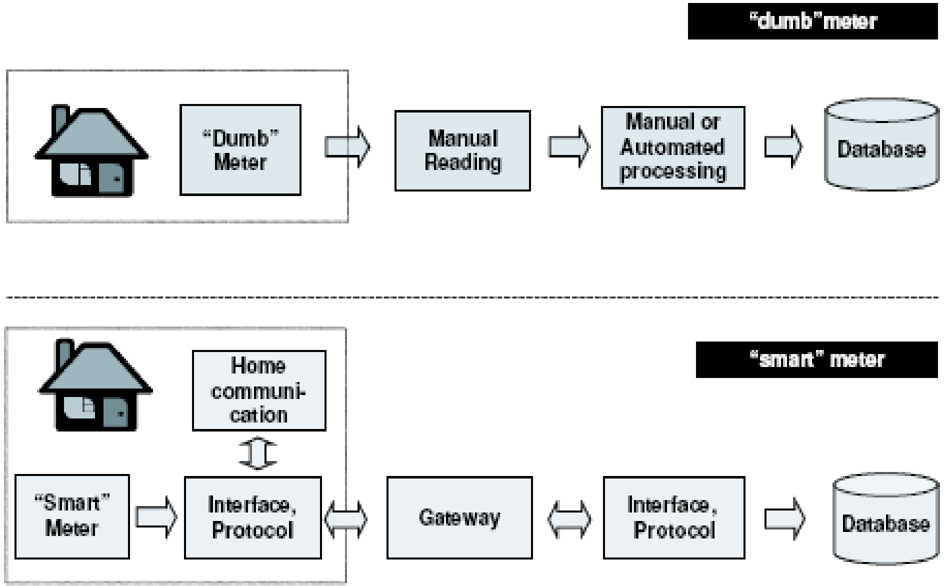
- ***PMUs Offer Wide-Area Visibility***
- Phasor Measurement Units will extend visibility across Eastern Interconnection
- Ability to triangulate the location of disturbances
- All were coordinated with reliability councils & ISOs–Ameren–Entergy–Hydro One

Automatic meter reading (AMR)

- Improved is Advanced Metering Infrastructure (AMI) or Smart meters (2-way)
- Used for revenue
- Wireless based
  - Many proprietary
  - Moderate range, drive-by reading
  - Mesh (Zigbee) and WiFi sometimes
  - Usually not Internet connected
- About 50M AMR/AMI installed (USA)
- Suggested standard: ANSI C12.18

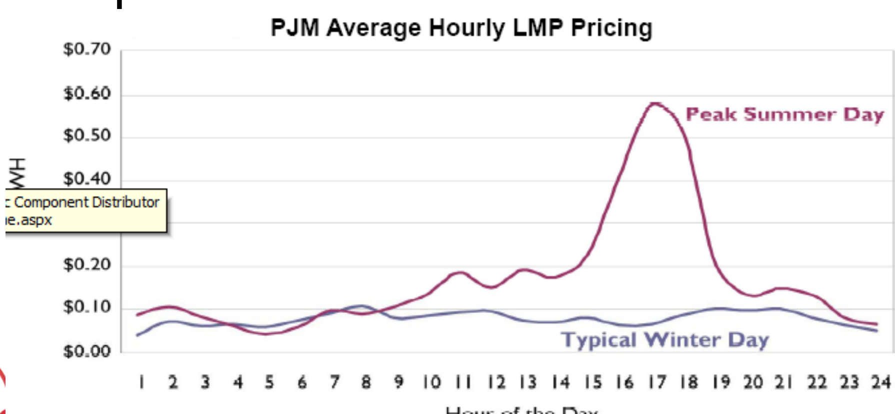
Energy Conservation

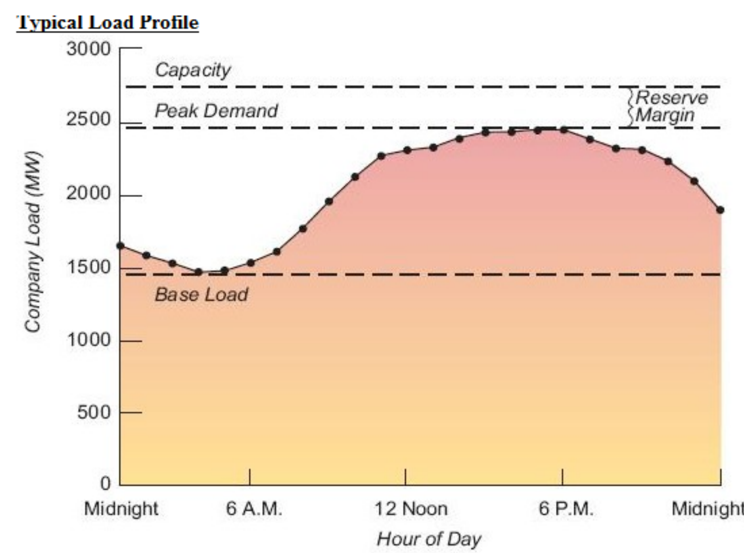
- Smart meters (at Microgrid level) provide information needed to analyze energy usage and thus allow energy minimization algorithms to be implemented
- Real time data, best at individual loads
- Control programs by utilities or private companies



Demand/Response

- Electrical load reduction (load shedding) in response to high demand on the grid (utilities issue alert)
- Purpose is to shave peak demand and reduce reserve power requirements (and build fewer power plants)
- Large rate increases during peak demand discourage consumption
- Implemented by utilities or third parties through contract (shed load when requested in return for lower rates)
- Requires smart meter at customer site





Summary of Topics Covered

- Overview of the Smart Grid
- Networked smart sensor design aspects
- Sensor networks
- Metering and power quality sensors
- Environmental and related sensors
- Time Synchronization
- Smart grid networked sensor standards
- Application areas

Contact: designer@eesensors.com

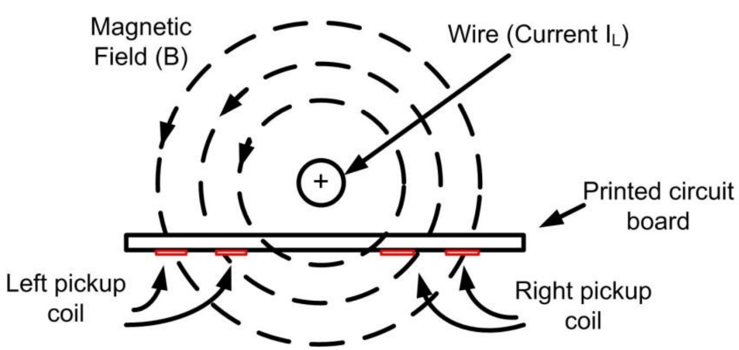
End

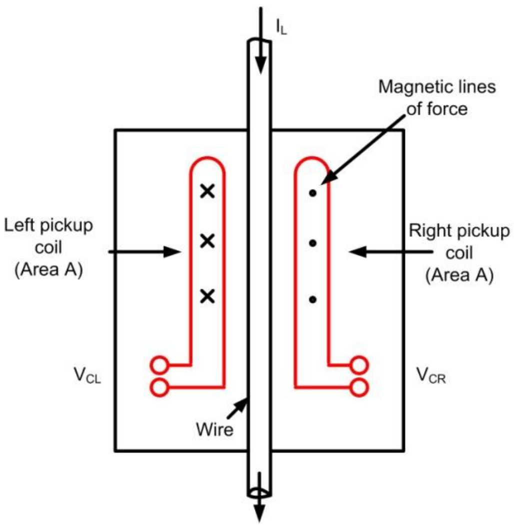
- Backup Slides Follow

www.eesensors.com

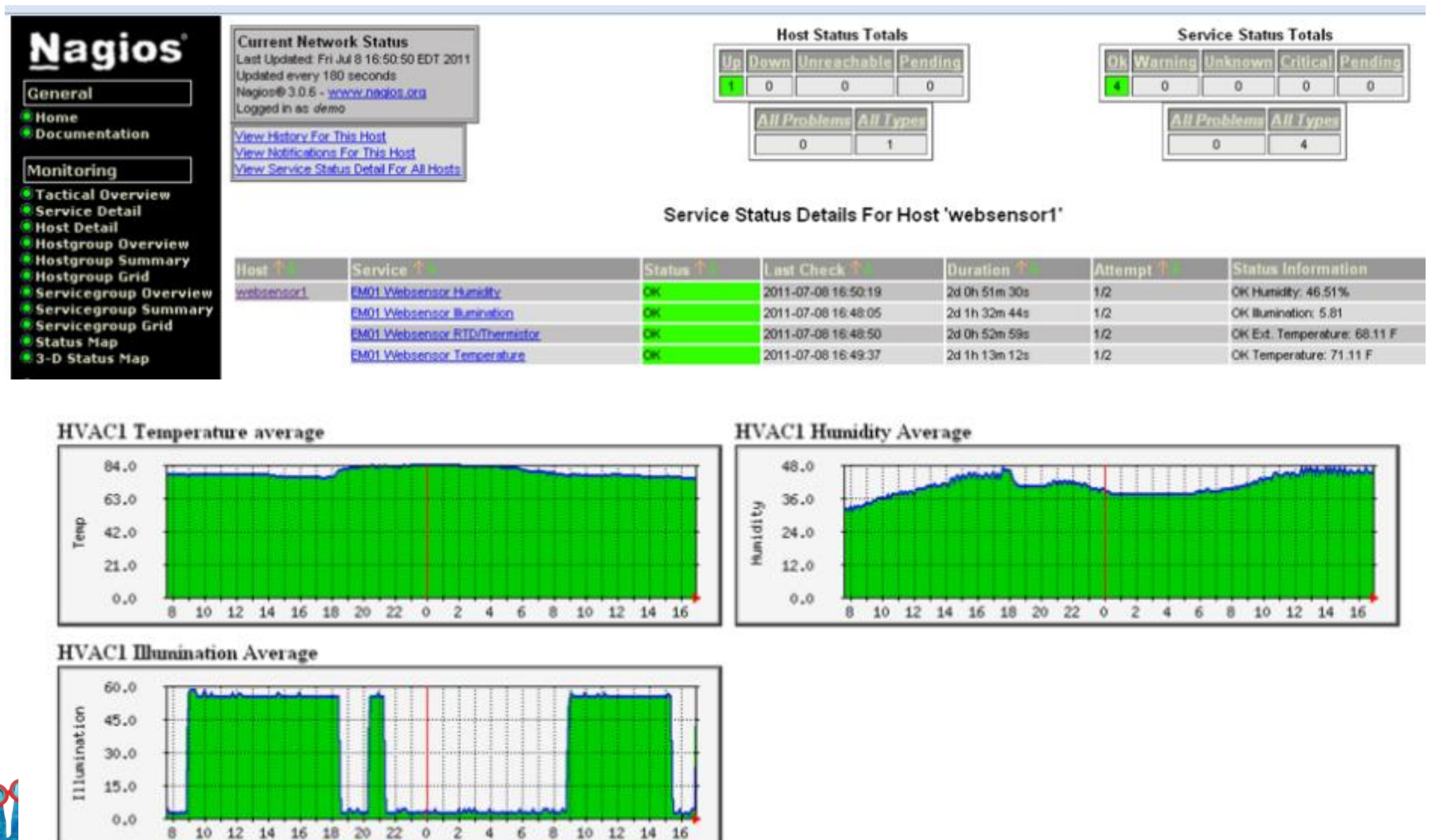
Inductive Pickup Current Sensor
(Esensors Product)

- Pickup is printed circuit board trace
- Voltage induced (e.g. .1 mv/amp) is proportional to AC current in wire
- Low cost, non-contact





Monitoring via Nagios



TECH FORUM

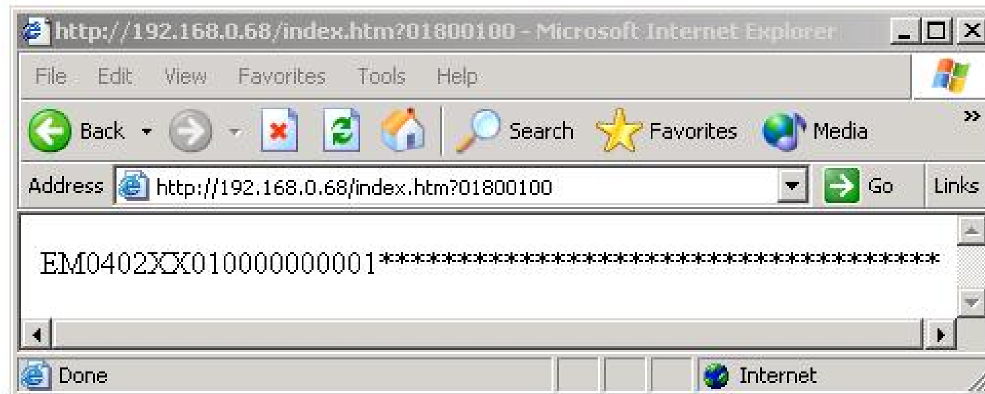
chall

IEEE 1451 Advantages

- Comprehensive enough to cover nearly all sensors and actuators in use today (not 20/80% approach)
- Many operating modes
  (buffered, no-buffer, grouped sensors, timestamps, timed data, streaming …)
- Extensive units, linearization and calibration options
- Multiple timing and data block size constraints handled.
- Compatible with most wired and wireless sensor buses and networks (point-to-point, mesh, TIM-to-TIM, mixed networks).
- Efficient binary protocol (especially suitable for wireless)
- Standard is 400+ pages for basic part, over 1500 page total

Data Readout Examples
(via Internet)

- Sensor data converted to ASCII for display



- TEDS data is displayed in hexadecimal form

Status of Various Parts of IEEE 1451

1451.0 – Basic data/TEDS format	**Done (2007)**
1451.1 – NCAP/Computer Interface	Done (1999)*
1451.2 – RS-232	Done (1997)*
1451.3 – Wired Multi-drop	Done (2002)*
1451.4 – TEDS Only	Done (2005)
1451.5 – Wireless (WiFi, Zigbee, etc)	Done (2007)
1451.6 – CAN Bus	In process
1451.7 – RFID	In process

Most used

* Needs revision

IEEE 1451.0 (Dot 0) TEDS Format

- Required TEDS [Memory block with defined format]
  - MetaTEDS
  - Channel TEDS
  - Calibration TEDS (unless SI units)
  - Xdr-name TEDS
  - Phy TEDS
  - Also optional TEDS

- Data Transmission [specific octet format]
  - TEDS/Status requests
  - Triggering and configuration
  - Sensor read commands and data return
  - Actuator write commands and data sending