2nd Smart Grid - Distribution Automation Conference

Network Sensor and System Monitoring Technologies

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Network Sensor and System Monitoring Technologies Agenda

- Application of Sensor Information
- Sensor Technologies
- Sensor Developments
- Communication and Sensor Data Collection
- Security
- Power Harvesting
- Algorithms and Data Visualization

Transmission Line and Substation Challenges

- Existing transmission lines and substations are aging while the required reliability is increasing and the availability of clearance to perform maintenance is decreasing.
- Need to maximize the utilization of the system, and thereby operate closer to the edge of reliability
- Need to increase the available capacity of the existing transmission system
- An increasing penetration of distributed generation and power electronics
- The shift to an intelligent grid with less traditional oil and iron-ore equipment and to more controllable solid-state and SF6 technologies. This new fleet of components will include automated smart diagnostics and condition assessment enabling the shift from resource-intensive time-based maintenance to more cost-effective condition-based maintenance.
- Need to integrate increasing amounts of renewable energy. These sources, especially wind, can be highly variable, intermittent and unpredictable.

Application of Sensor Information

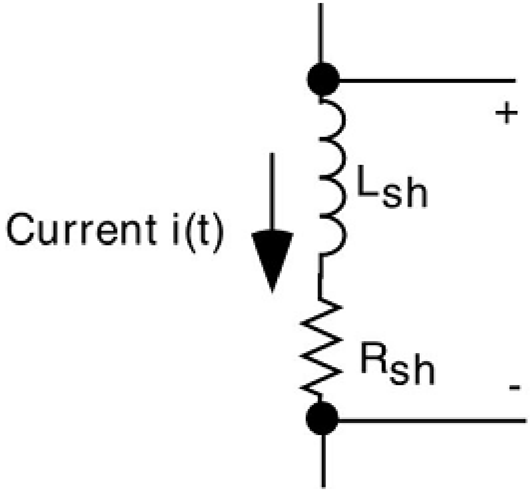
- Operations – real-time power flow especially with DG
- Safety - monitoring and communication of equipment conditions continuously
- Personnel Deployment to prevent or repair an outage
- Condition Based Maintenance - enables maintenance actions to be initiated at appropriate times
- Asset Management - improved knowledge of the condition of equipment and stresses that they have been subjected to
- Increased Asset Utilization - real time knowledge of the components condition allows for higher dynamic ratings
- Forensic and Diagnostic Analysis – sensors provide the information needed to identify the root cause
- Operations Improvement - increased utilization of the grid is possible if contingency analyses performed probabilistically

Sensor Technologies

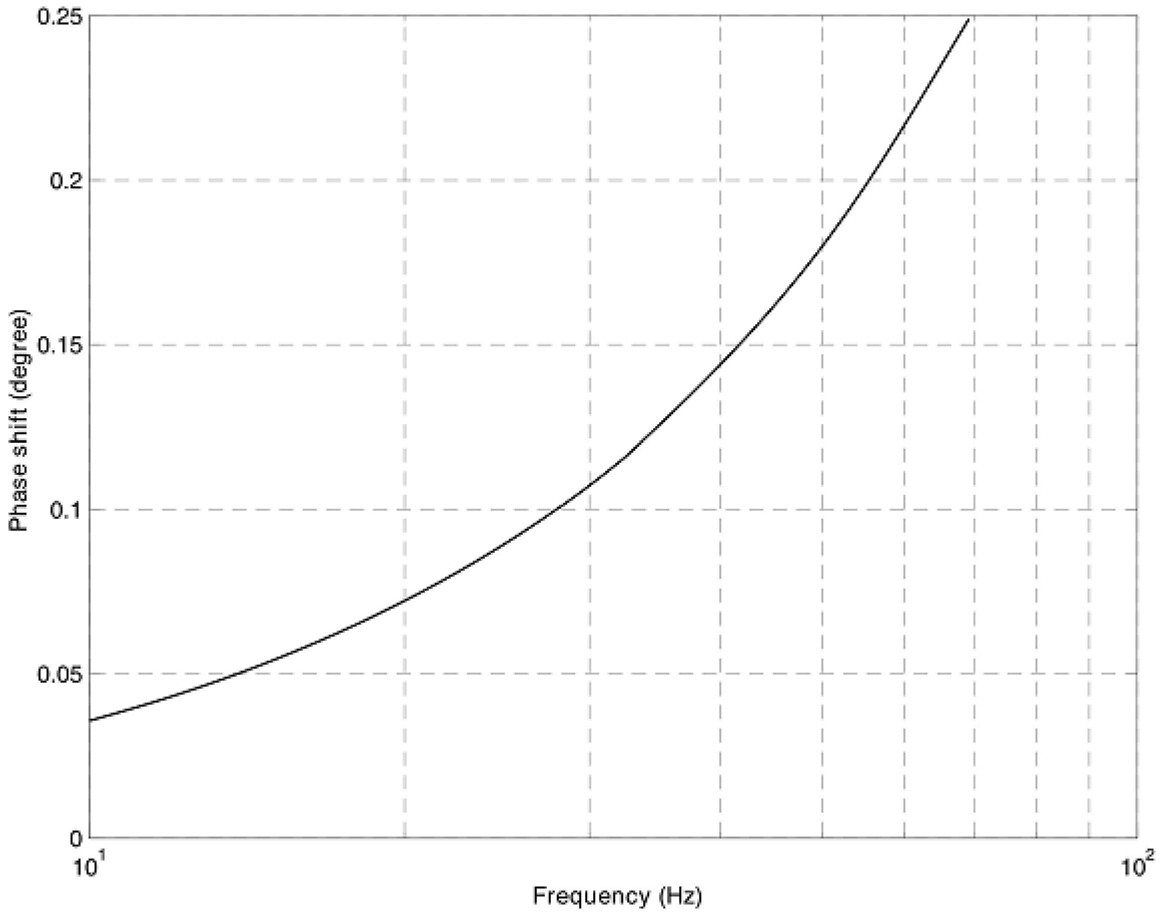
- Current
- Voltage
- Phase
- Frequency
- Insulation
- Temperature
- Smart Sensors

Low Resistance Current Shunt

- Current shunt is the lowest cost solution
- Offers good accuracy
- Heat prop i^2
- The parasitic inductance of the shunt must be considered when performing high precision current measurements



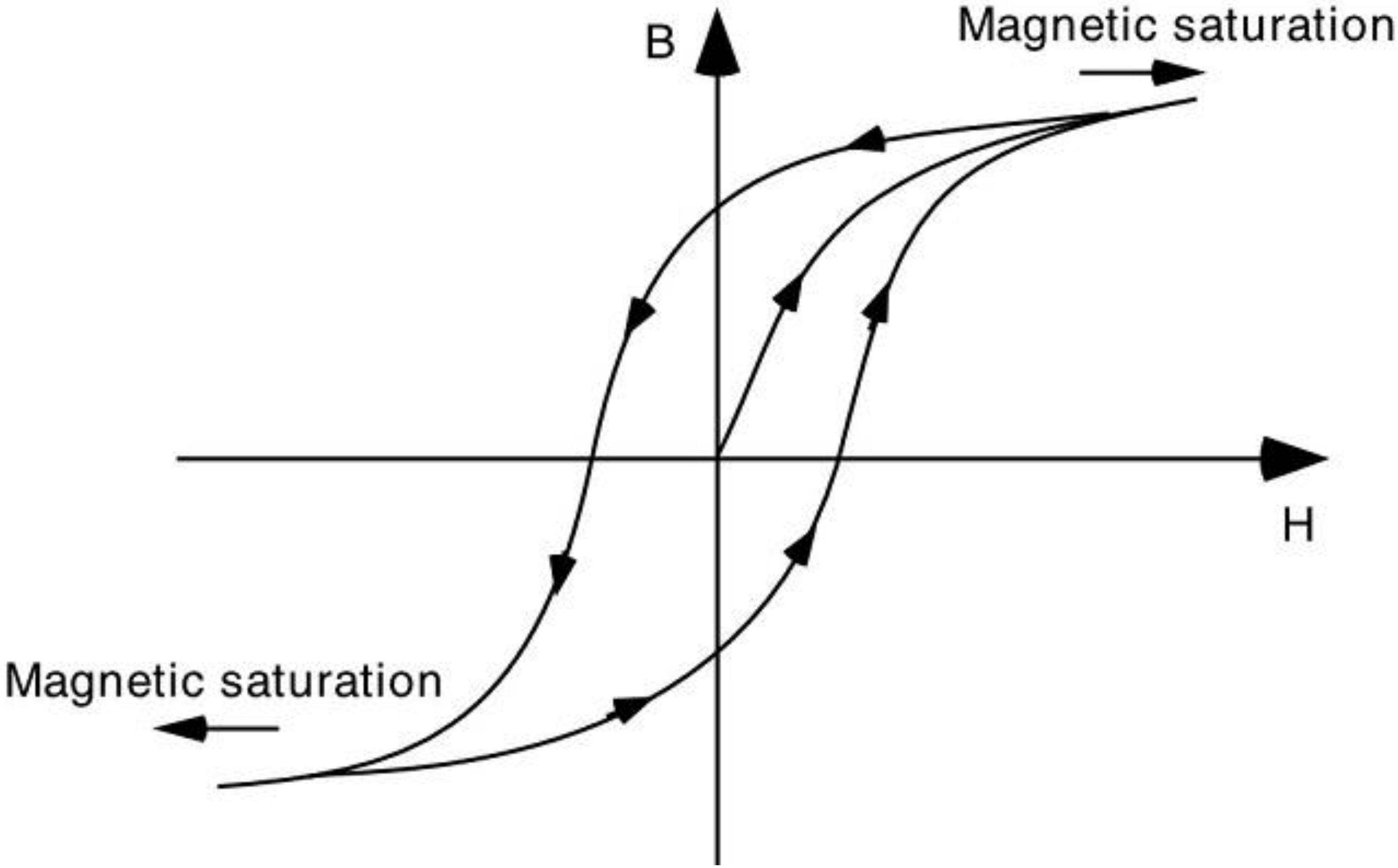
Phase Shift Caused by Self-inductance (2nH / 200μΩ Shunt)



Current Transformer (CT)

- Transformer which converts the primary current into a smaller secondary current. $I_1 \times N_1 = I_2 \times N_2$
- CT is the most common sensor
- CT can measure up to very high current and consumes little power
- CT typically have a small phase shift associated with it (0.1°-0.3°) due to the magnetizing current
- CT ferrite material used in the core can saturate at high current

Hysteresis Curve of a Ferrite Material



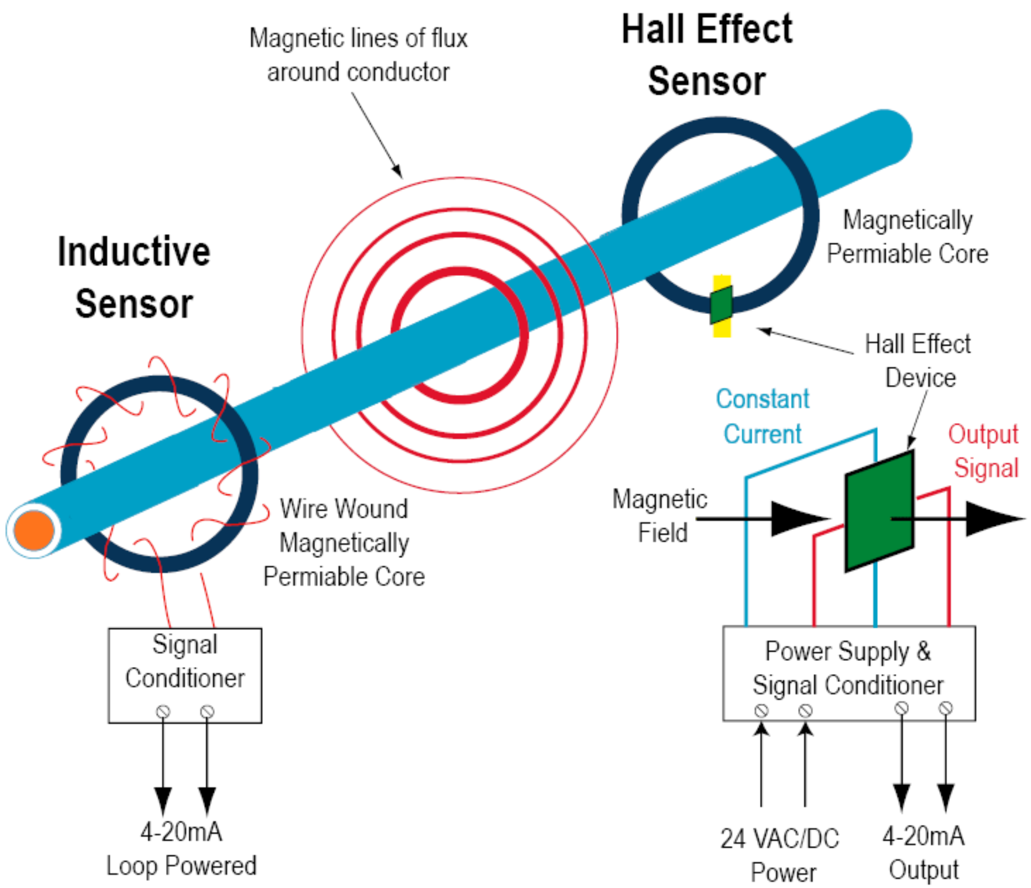
CT Saturation

- CT saturation can occur when current surges beyond a CT's rated current, or when there is substantial dc component in the current (e.g. when driving a large half-wave rectified load)
- Solution to the saturation problem is to use ferrite material with very high permeability such as using Mu-metal core.
- This type of CT's has inconsistent and larger phase shift compared with the conventional iron core CT's.

Hall Effect Sensor

- There are two main types of Hall effect sensors: open-loop and closed-loop implementation.
- Most Hall effect sensors found in energy meters use open-loop design for lower system cost.
- Hall effect sensor has outstanding frequency response and is capable of measuring very large currents
- The output from Hall effect sensor has a large temperature drift and it usually requires a stable external current source.
- Needs a power supply – higher cost than CT

Current Sensing - Hall effect & Induction

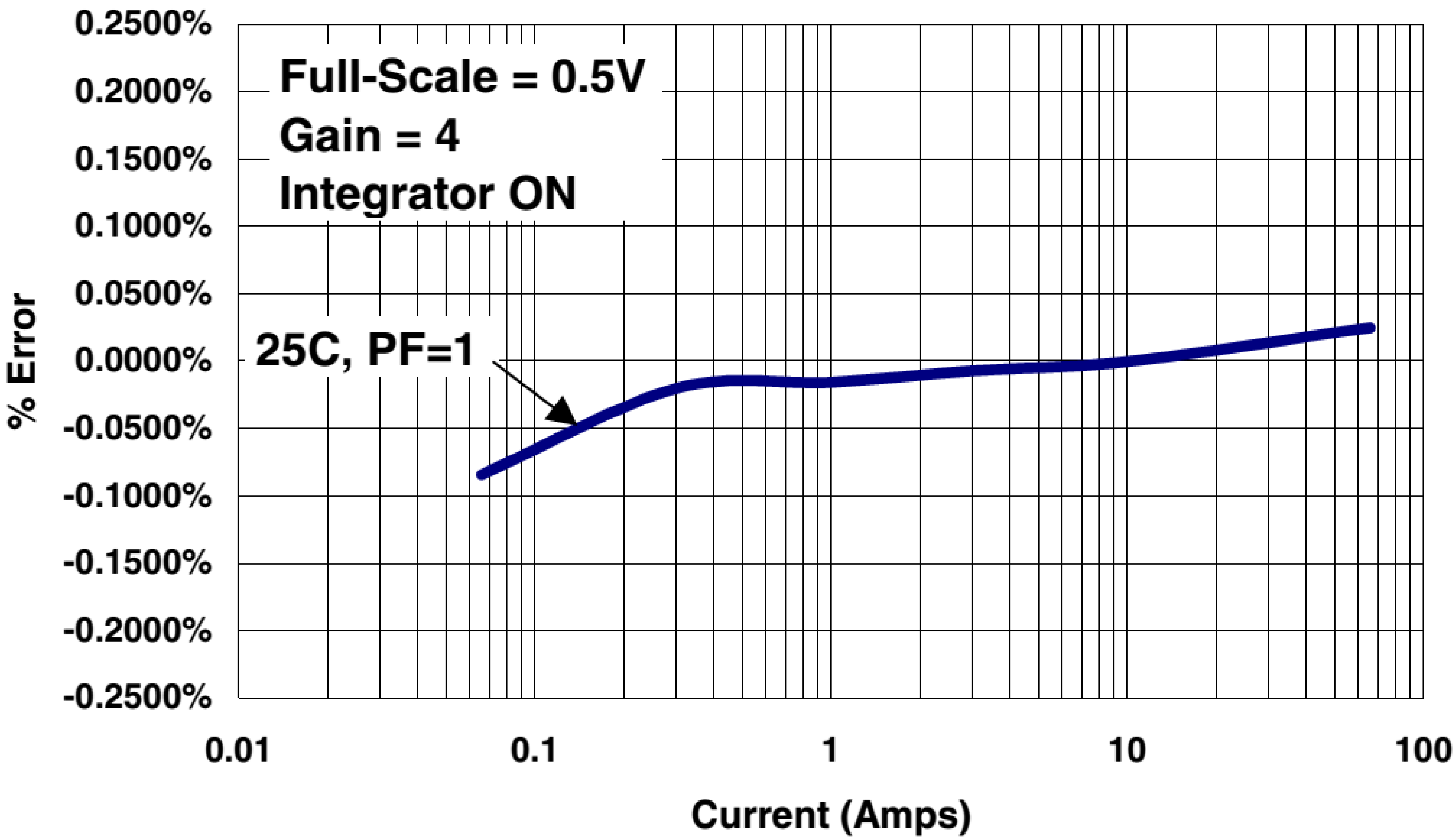


http://www.nktechnologies.com/current-sensing.html

Rogowski Coil

- A simple Rogowski coil is an inductor which has mutual inductance with the conductor carrying the primary current.
- Rogowski coil is typically made from air-core coil so in theory there is no hysteresis, saturation, or non-linearity
- The basic operating principle of a Rogowski coil is to measure the primary current through mutual inductance
- The Rogowski coil relies on measuring magnetic field which makes this type of current sensor susceptible to external magnetic field interference compared with the CT

Linearity Accuracy of Rogowski Coil



Rogowski Coil to Measure AC or Fast Transient Currents

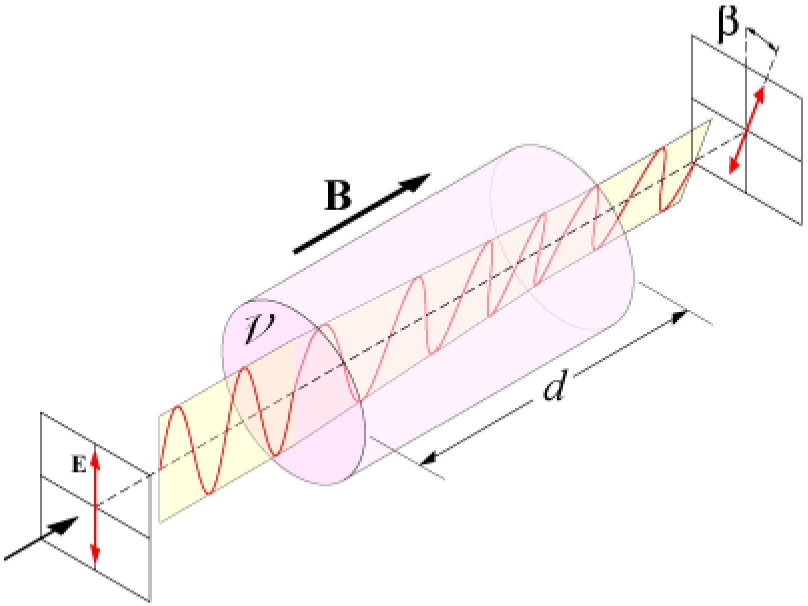
- Simple to retro-fit - the clip-around sensor is thin, lightweight, flexible and robust
- Coil size is not dependant on the magnitude of the current
- Non-Intrusive
- Wide-bandwidth with predictable frequency response, ideal for power quality measurement or monitoring complex waveforms
- Galvanic isolation
- Excellent linearity
- Capable of huge overload currents without damage
- Immune to DC Currents

Comparison of Current Sensing Technologies

Current Sensing Technology	Low resistance current shunt	Current Transformer	HallEffect Sensor	Rogowski Coil
Cost	Very Low	Medium	High	Low
Linearity over measurement range	Very Good	Fair	Poor	Very Good
High Current measuring capability	Very Poor	Good	Good	Very Good
Power consumption	High	Low	Medium	Low
DC/high current saturation problem	No	Yes	Yes	No
Output variation with temperature	Medium	Low	High	Very Low
DC offset problem	Yes	No	Yes	No
Saturation and Hysteresis problem	No	Yes	Yes	No

Magneto-Optical (MO) Effect

- Magneto-optical phenomenon is an interaction between light and a magnetic field.
- The **Faraday effect** or **Faraday rotation** is a magneto-optical phenomenon



Fibre Optic Current Sensor (FOCS)

- In 2013 ABB launched a 420 kV Disconnecting Circuit Breaker with integrated FOCS.
- With FOCS replacing the conventional current transformer the engineering and design of the substation is simplified, since one FOCS replaces many current transformer cores.
- Since utilizing FOCS reduces the material needed and eliminates the need of additional insulation medium, a 420 kV DCB with integrated FOCS can reduce a substation’s footprint with over 50 % compared to a conventional solution of live tank breakers with disconnectors and current transformers

DC Breaker with FOCS

http://en.wikipedia.org/wiki/File:DCB_with_FOCS.jpg

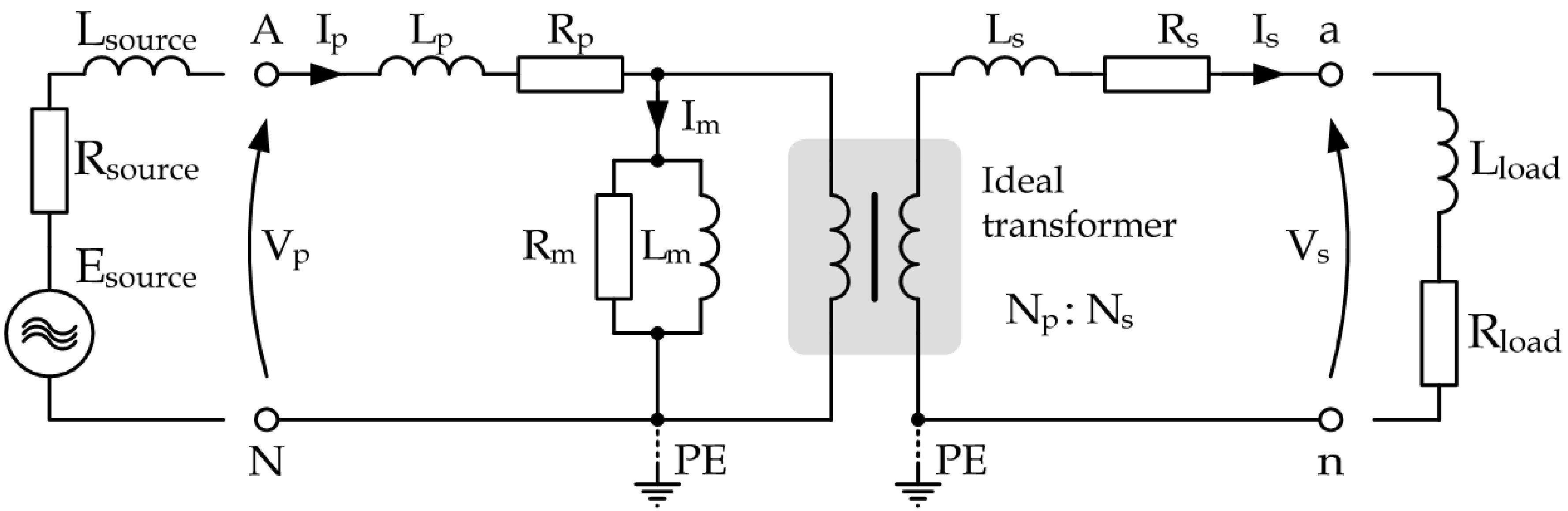
Voltage Transformer (VT / PT)

- Similar to conventional transformer with care to minimise errors and power transformed is low
- Input to output proportional to turns ratio

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

- Widely used

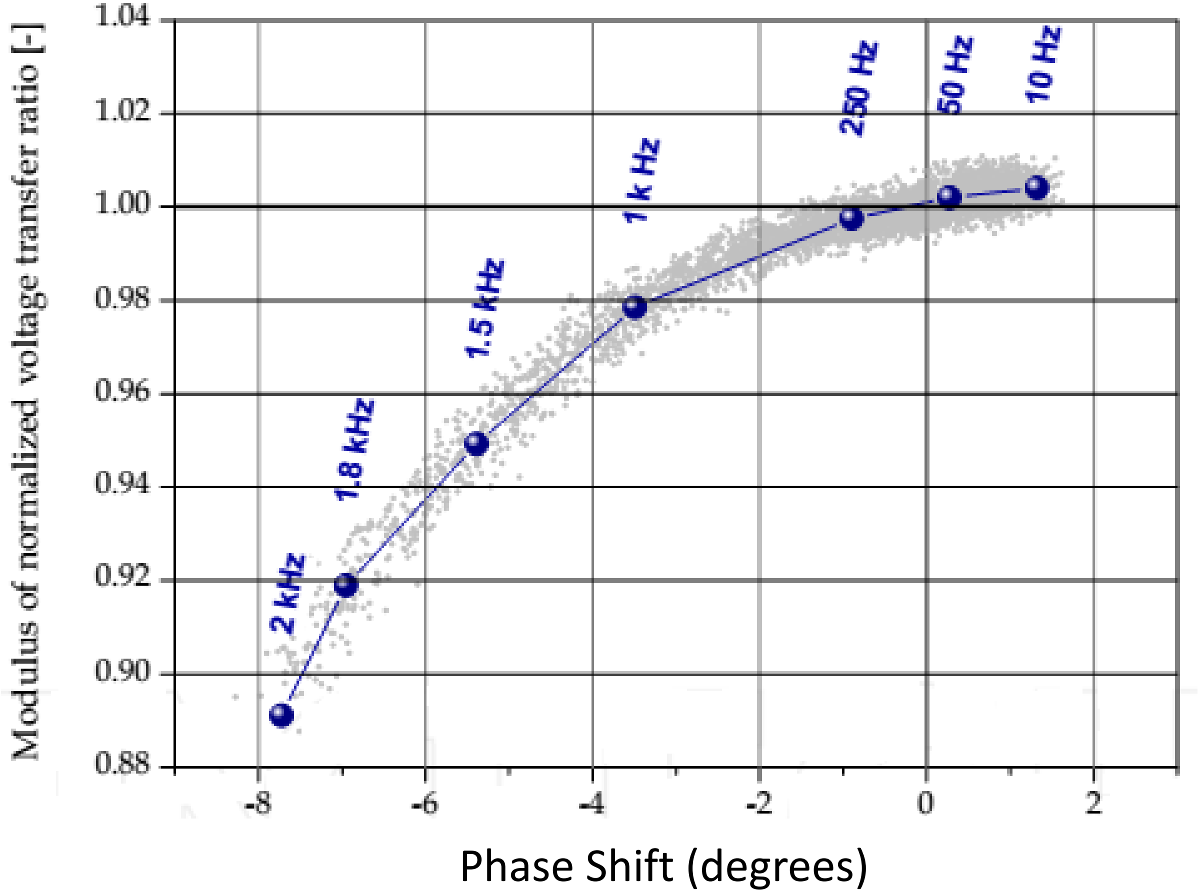
Equivalent Circuit Model of a Voltage Transformer



VT Errors

- Voltage (Ratio) errors
- Burden errors
- Phase angle errors
- Saturation
- Frequency Response

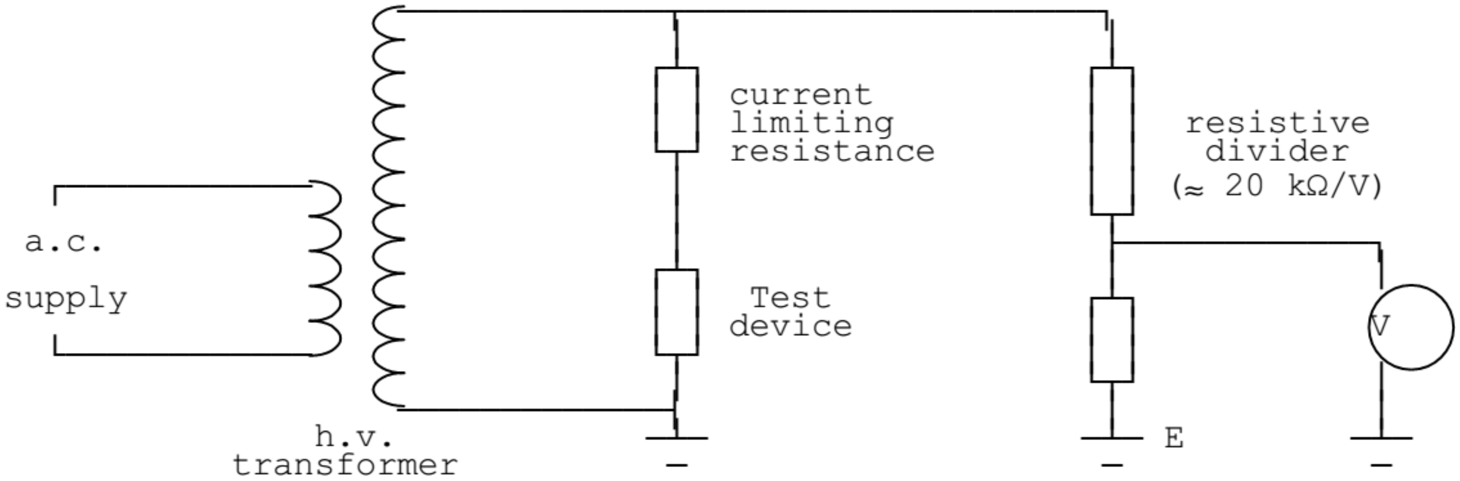
Normalized VT Voltage Ratio vs. Phase Shift Angle



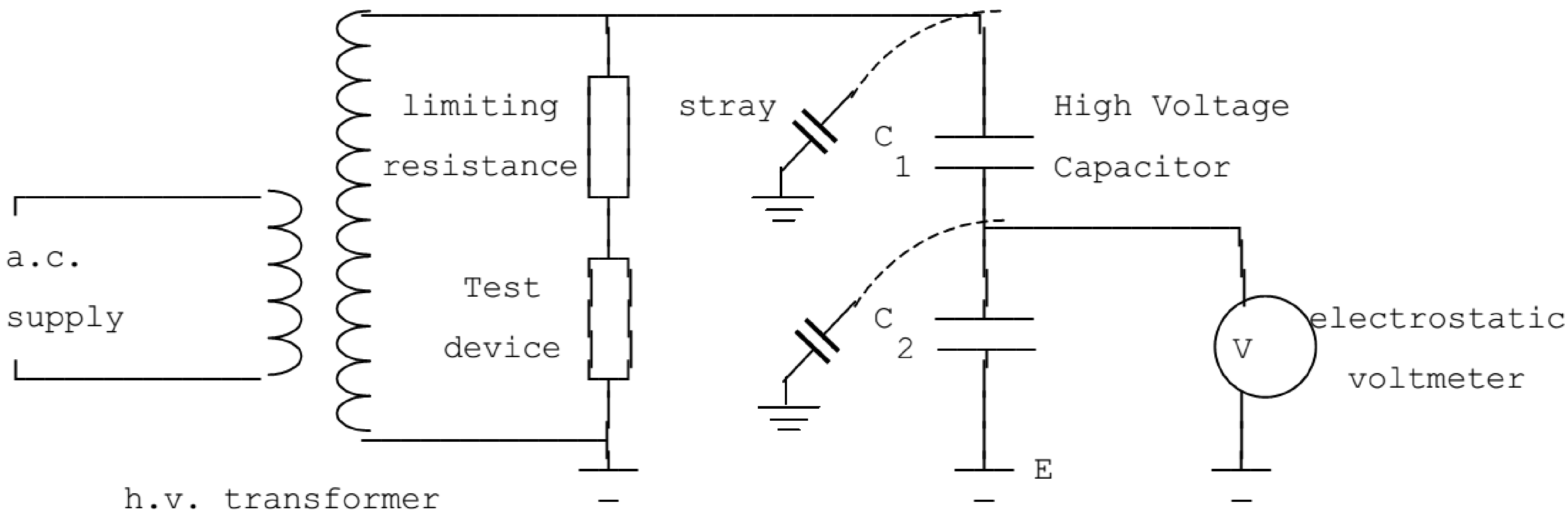
VT Ferroresonance

- Star connected VT's on ungrounded power systems
  - VT is inductive
  - Capacitance to ground
  - Ferroresonance can occur when $X_L = X_C$
- Causes higher VT voltages and saturation
  - Results in higher VT currents
  - Overheating
  - VT Failure
- Add damping resistor

Resistive Potential Divider

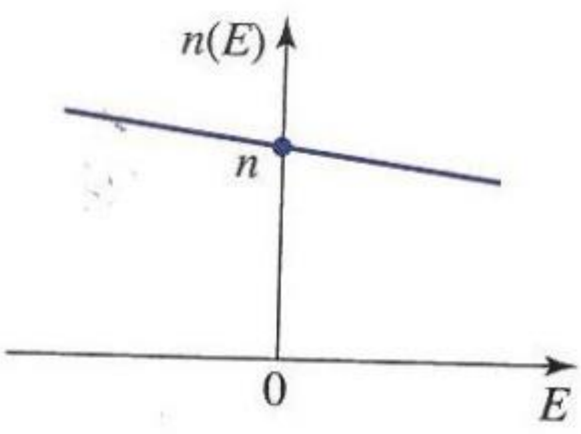


Capacitive Voltage Divider

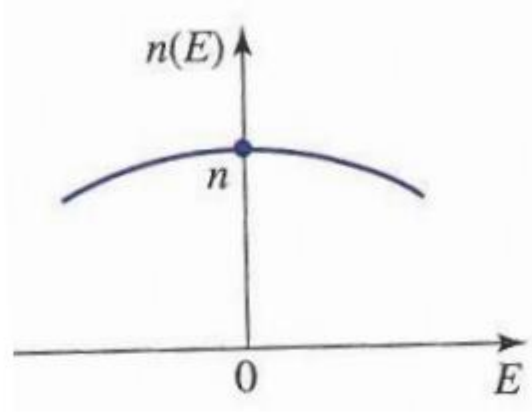


The Electro-Optic (EO) Effect

- The electro-optic (E-O) effect is a 2nd-order nonlinear optical effect that results in a refractive index that is a function of the applied electric field (voltage)



Pockels Effect

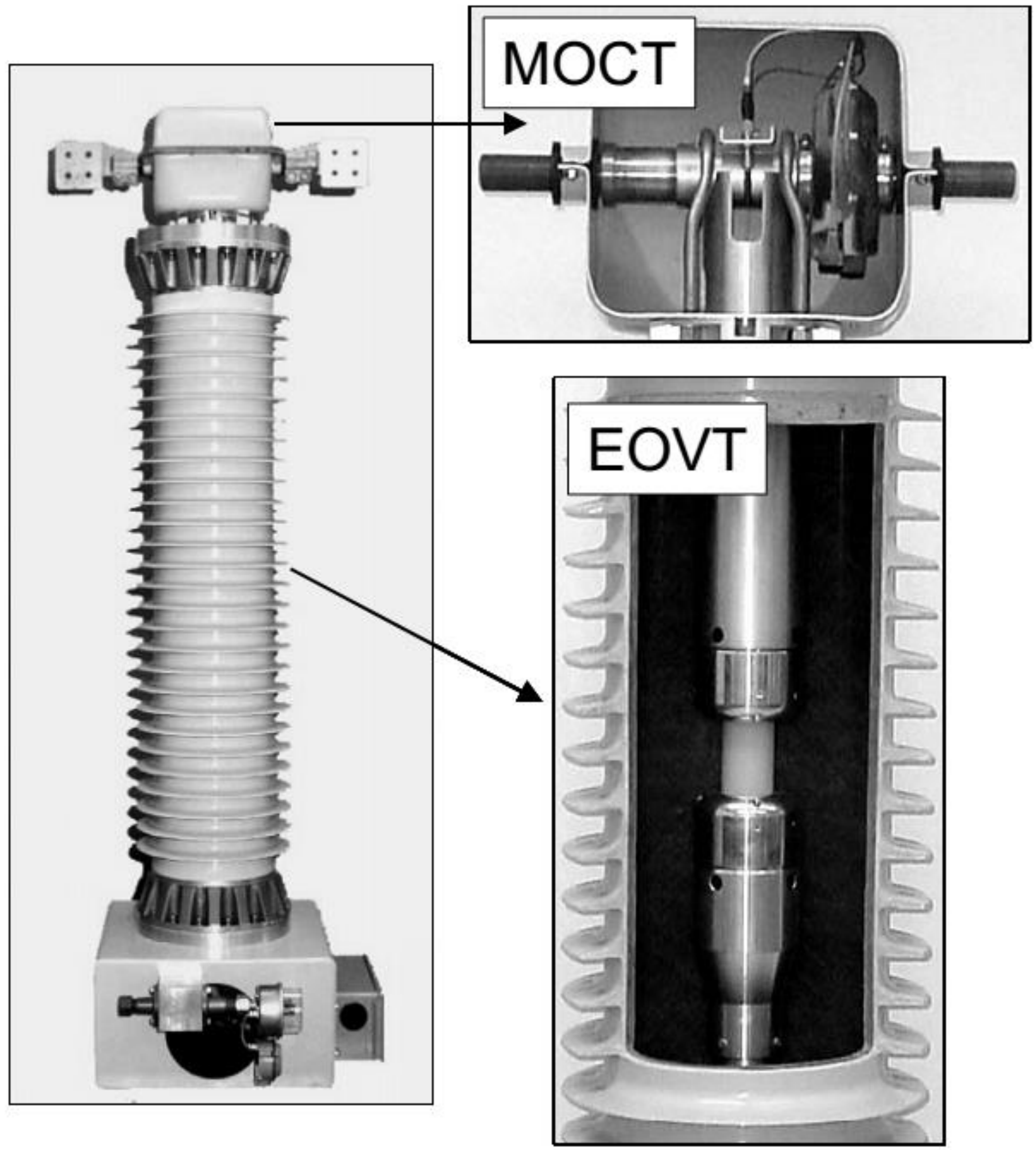


Kerr Effect

Optical Voltage Sensors (OVS)

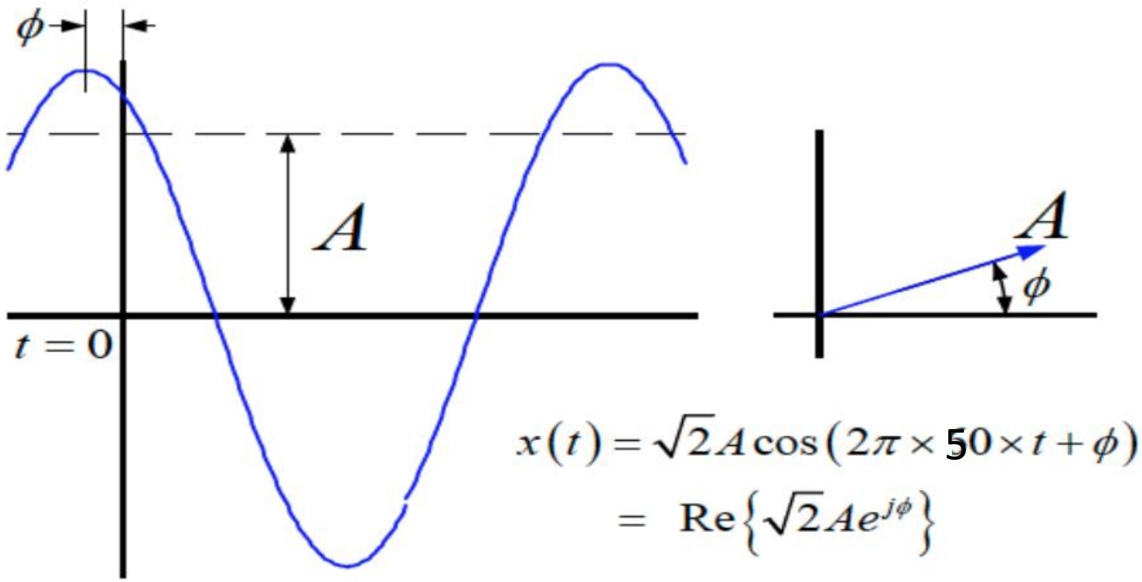
- Can use conventional sensor with optical output
- Use linear electro-optic (Pockels) effect – essentially electric field sensors
- Various means of getting relationship between applied voltage and electric field

170 kV Circuit Breakers with Integrated Optic Transducers



Phasor

- Phasor: A sinusoidal signal can be represented by a cosine function with a magnitude A, frequency ω, and phase Φ

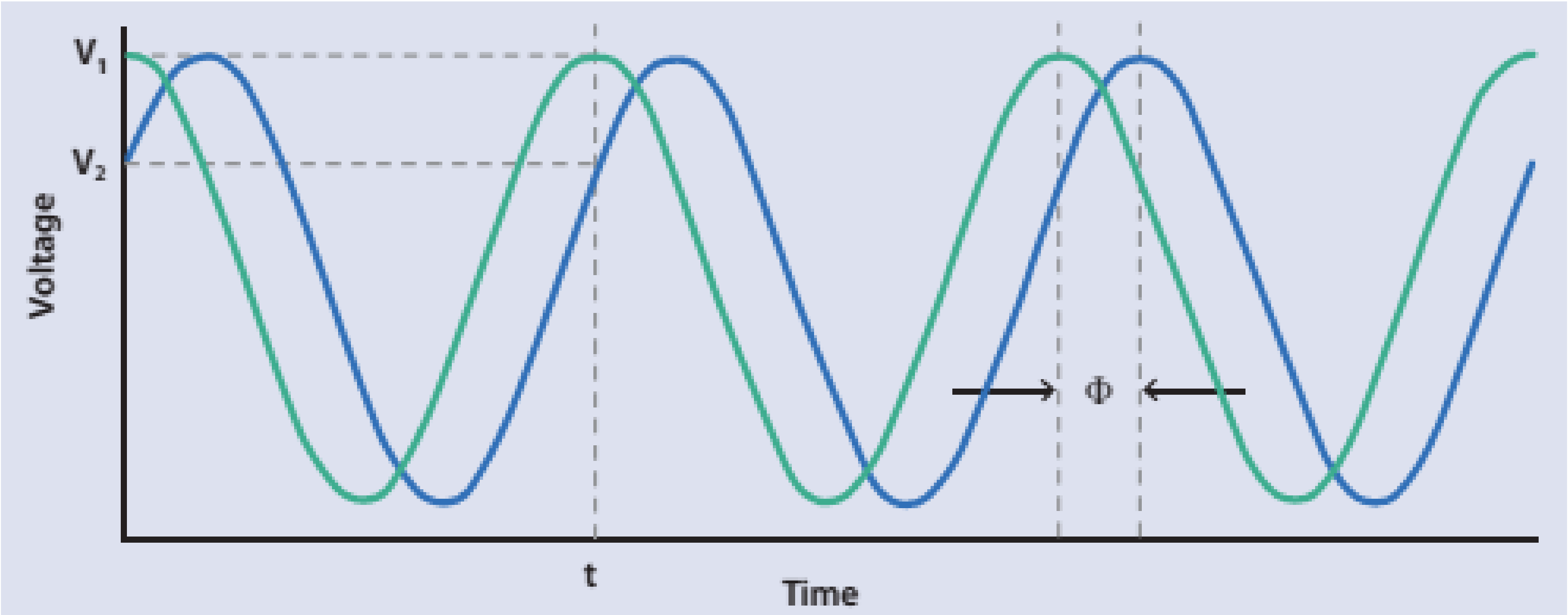


$$x(t) = \sqrt{2} A \cos(2\pi \times 50 \times t + \phi)$$
$$= \mathrm{Re}\left\{\sqrt{2} A e^{j\phi}\right\}$$

Phase Measurement

- Angle between voltage and current represents flow of active and reactive power
- Angle between voltage or current measurement devices at various parts of the grid can be used to detect abnormal waveshapes or fault conditions

Phase Angle Difference (ϕ) of Voltage Sinusoids at the Ends of a Transmission Line

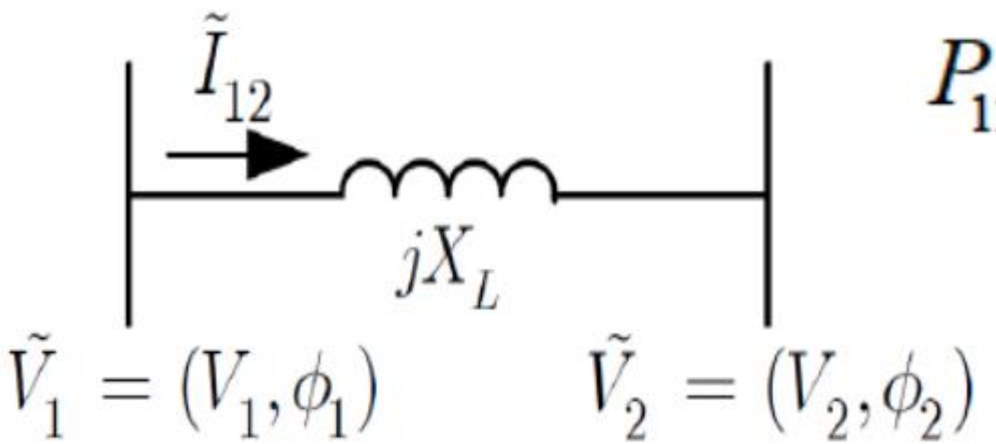


Power Flow

- Two factors determine power flow: the impedance of a line and the difference in the instantaneous voltages at its two ends
- The power flow on a line varies directly with the phase angle difference (or more precisely the sine of the phase angle difference) and inversely with the line’s impedance

Synchrophasor

- P,Q flow can be computed from the synchronized measurement of the adjacent bus voltage phasors at the same time instant
- The two voltage phasors have to be measured at exactly the same time



$$P_{12} = \frac{V_1 V_2 \sin(\phi_1 - \phi_2)}{X_L}$$

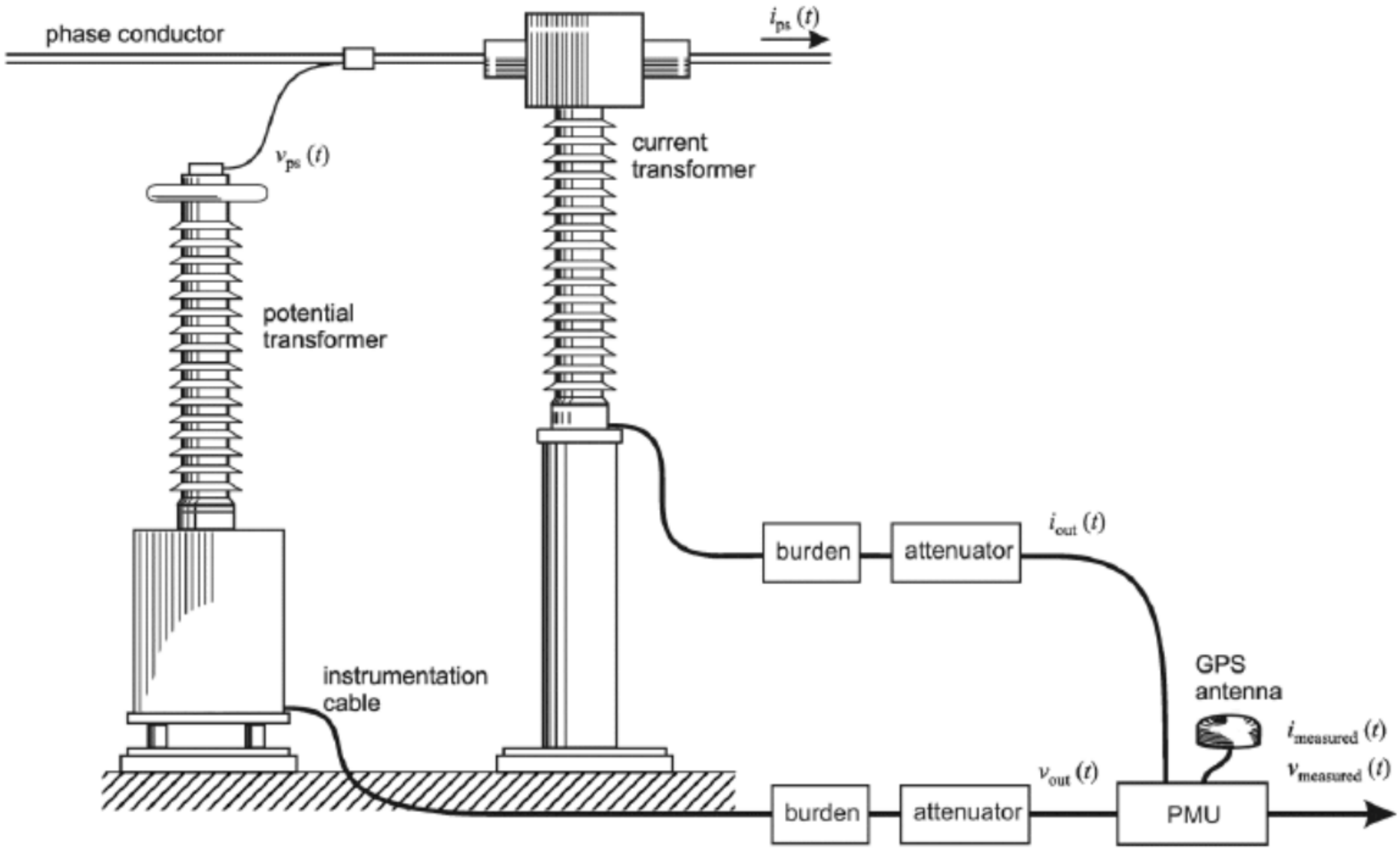
Phasor Measurement Unit (PMU)

- PMU) has been defined by the IEEE as “a device that produces Synchronized Phasor, Frequency, and Rate of Change of Frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal
- Phasor Measurement Unit (PMU) – A transducer that converts three-phase analog signal of voltage or current into Synchrophasors

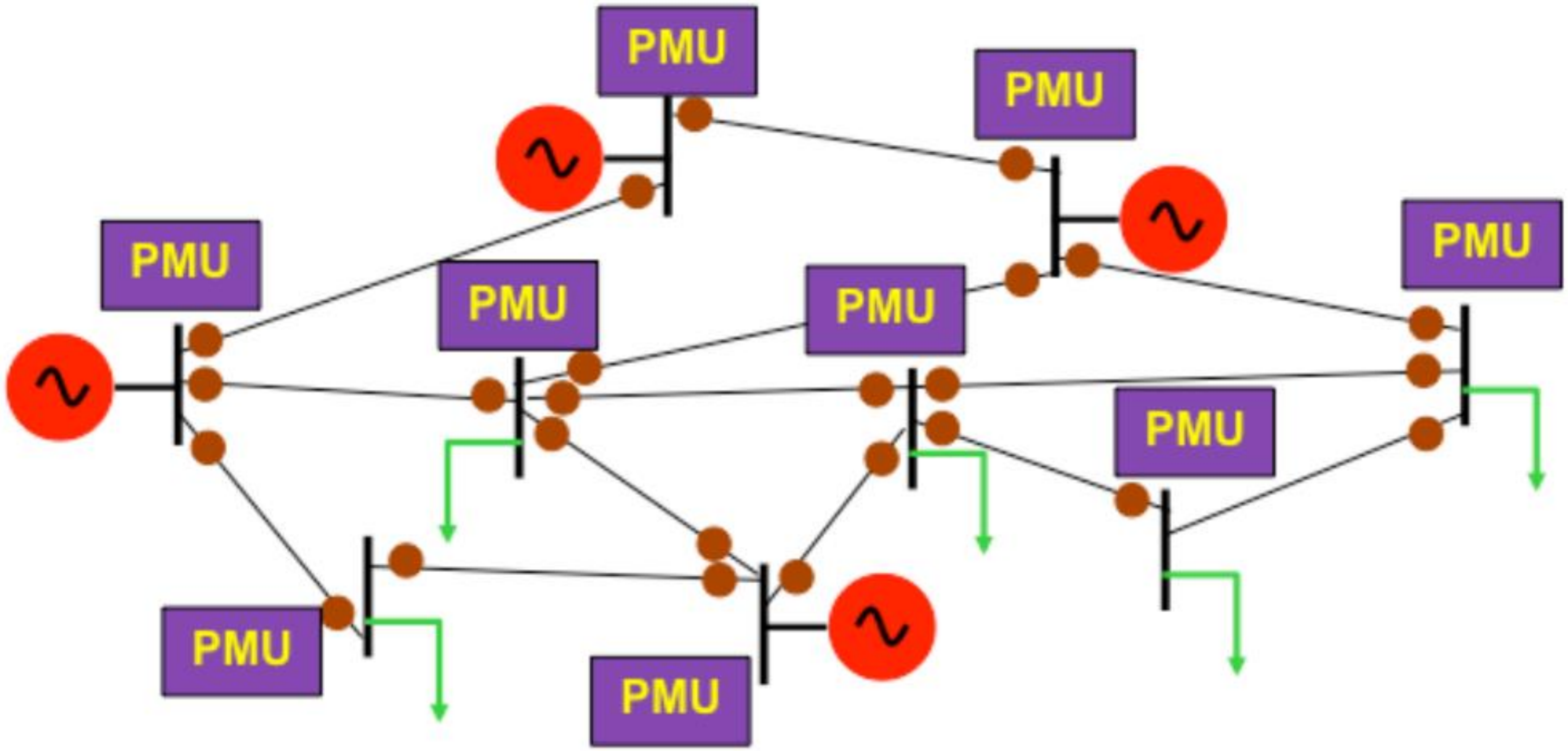
PMU Measurements

- PMUs measure (synchronously):
  - Positive sequence voltages and currents
  - Phase voltages and currents
  - Local frequency
  - Local rate of change of frequency
  - Circuit breaker and switch status

PMU Instrumentation



PMU Deployment



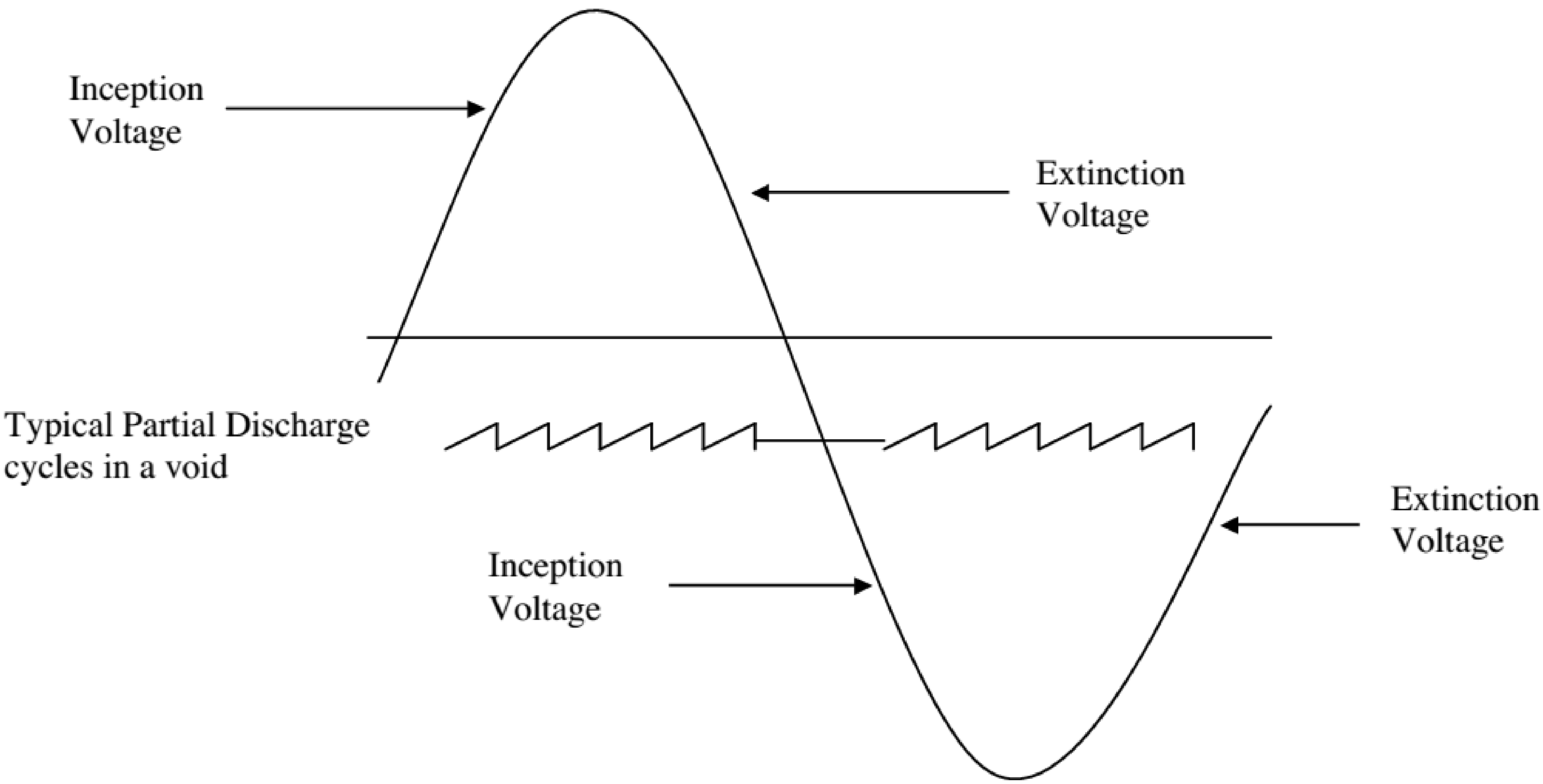
Insulation

- There could be no electrical power distribution without electrical insulation
- The higher the potential, the greater the level of insulation required
- The life span and consequently the ability of electrical equipment to operate reliably is fundamentally determined by the condition of the insulation.

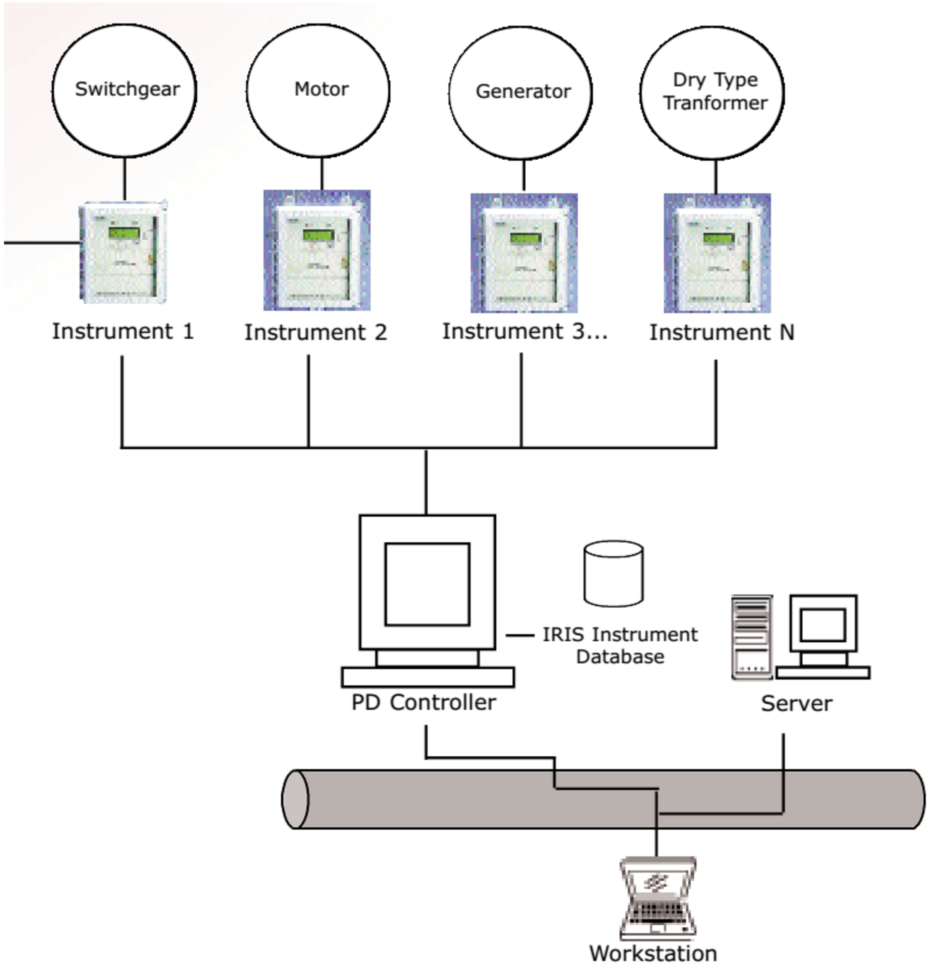
Insulation Measurement

- Offline
  - Insulation Resistance
  - AC and DC overvoltage testing
  - Dissipation Factor / Loss factor / Tan δ
  - Surge and impulse tests
  - Partial Discharge (PD)
- On-line
  - PD
  - Current signature analysis

Inception and Extinction of Partial Discharge



On-Line PD Monitoring



PD Measurement with Wireless Wideband RF

- PD has been detected using a wide range of sensor technologies including acoustic, ultrasonic, infra-red and electrical.
- Each of these sensors requires physical contact with the plant being monitored and each item of plant, therefore, requires (at least) one dedicated sensor
- The pulse-like nature of PD and their short duration results in radio frequency (RF) components which are readily radiated either from the discharge site directly or from conductors leading away from the site.
- This makes possible the wireless detection of PD using an appropriate, broadband, radio receiver.
- Wireless detection of PD using a radio receiver has the advantage that no physical connection need be made to HV (or any other) equipment

Substation Wide Antenna Arrays

Temperature

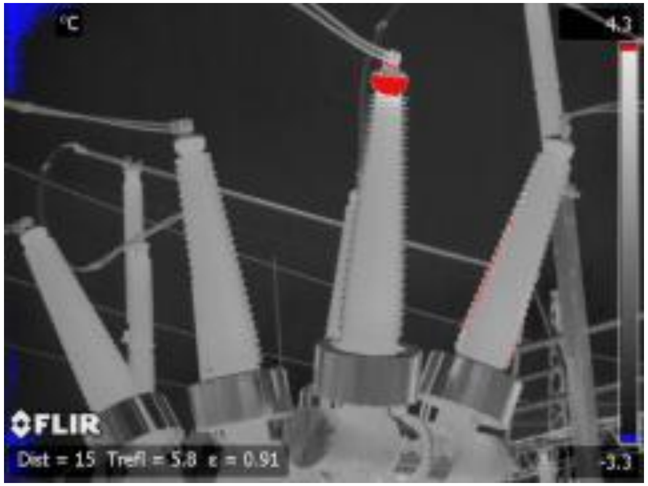
- Electrical equipment dissipates heat as a normal part of its operation – fixed losses + load dependent losses.
- Insulation life is dependent on the operating temperature. (Life halves for every 10 deg C above rated insulation temp)

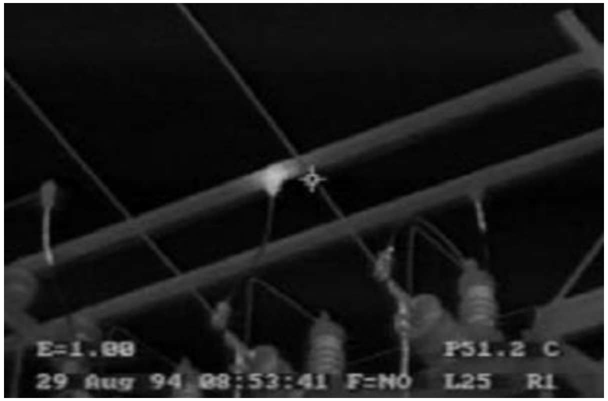
Temperature Measurement

- Contact
  - Thermocouple
  - RTD
  - Thermistor
- Non Contact
  - Infra Red (portable and fixed)

IR Substation Monitoring

- Infrared thermography detects hot spots produced when there is an electrical anomaly
- NB - Infrared cannot detect the presence of corona discharge – use ultrasonic measurement





Smart Sensors

- Stand alone sensors that are self powered or employ energy harvesting and communicate wirelessly
- They can be deployed with minimal infrastructure

Smart Sensor Examples

- Transformer-3D Acoustic Emissions -detection and location of gassing sources in power transformers and LTCs
- Transformer-Acoustic Fibre Optic - measurement of internal partial discharges using fibre optics installed in high risk regions of a transformer
- Conductor – RF Temperature and Current Sensor - sensor records overhead transmission conductor temperatures and current magnitudes and wirelessly transmits the information for rating applications. These sensors power harvest from the magnetic field.
- Overhead Insulator RF Leakage Current Sensor- measures the leakage current levels and provides an indication of when to wash insulation or when a high risk of flashover exists

New Sensor Developments

- Ongoing R & D to
  - Identify and develop new sensor technologies
  - Improve cost effectiveness
  - Increase reliability
  - Understand and expand applications

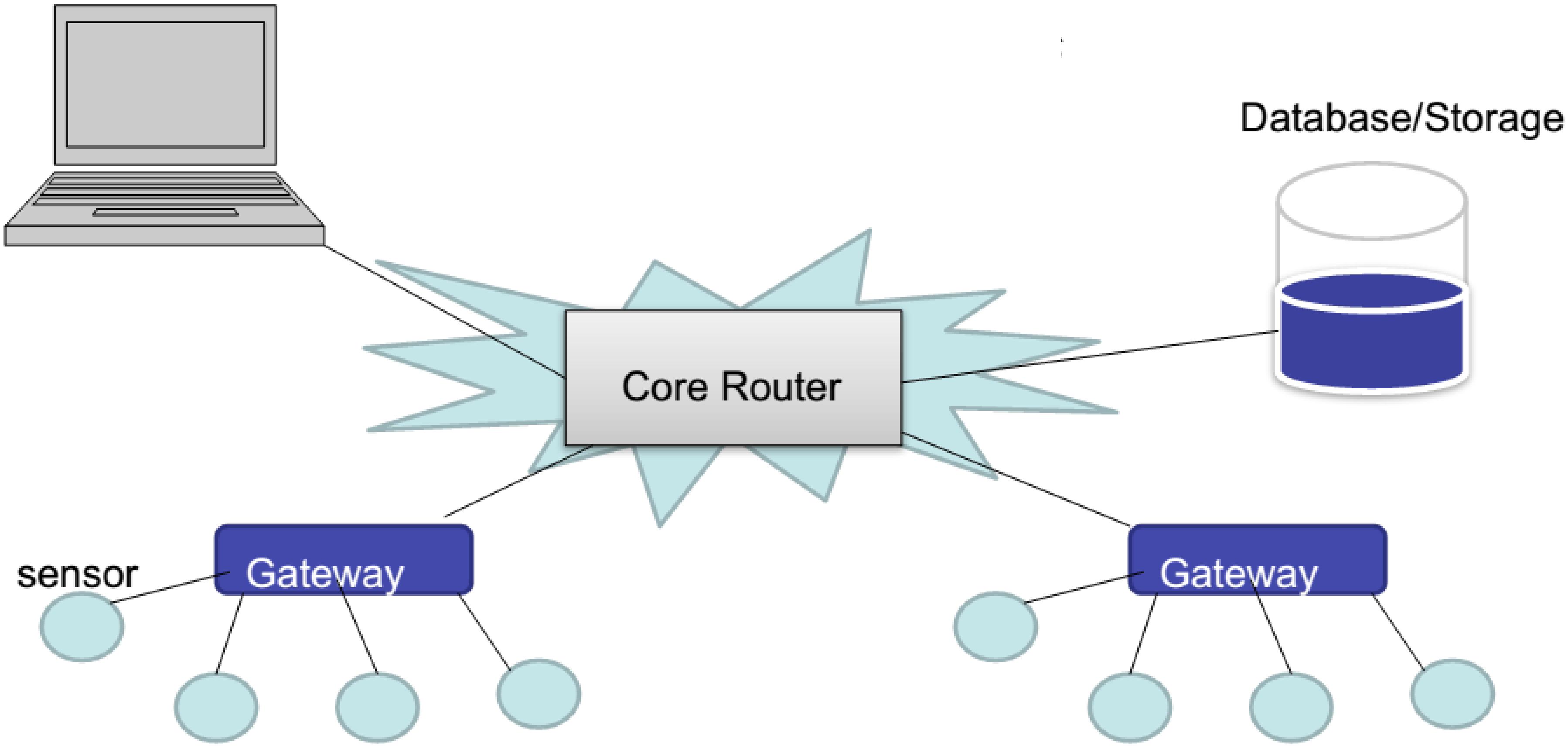
Communication and Sensor Data Collection

- Substations
  - Wired
  - Wireless Sensor Mesh
  - Wireless Point to Point
- Transmission Lines
  - Direct Communication from Sensors (Radio / Satellite, GSM)
  - Acquire, store & transfer during periodic inspection
  - Wireless Transmission Line Hub
  - Transmission Line Robot
  - Mesh / Daisy Chain

Wireless Sensor Networks (WSNs)

- Sensor networks capture valuable data for controlled networks, integral to smart grid development
- Wireless Multimedia Sensor Networks include various high-tech researched sensors, multimodal cameras (radiation detection, sunlight, wind, temperature, etc…)
- Low Cost compared to wired counterparts (wiring cost included)
- Currently Utilized in military applications, environmental monitoring, commercial and human centric applications
- Smart Grid is about information – sensors provide all the information

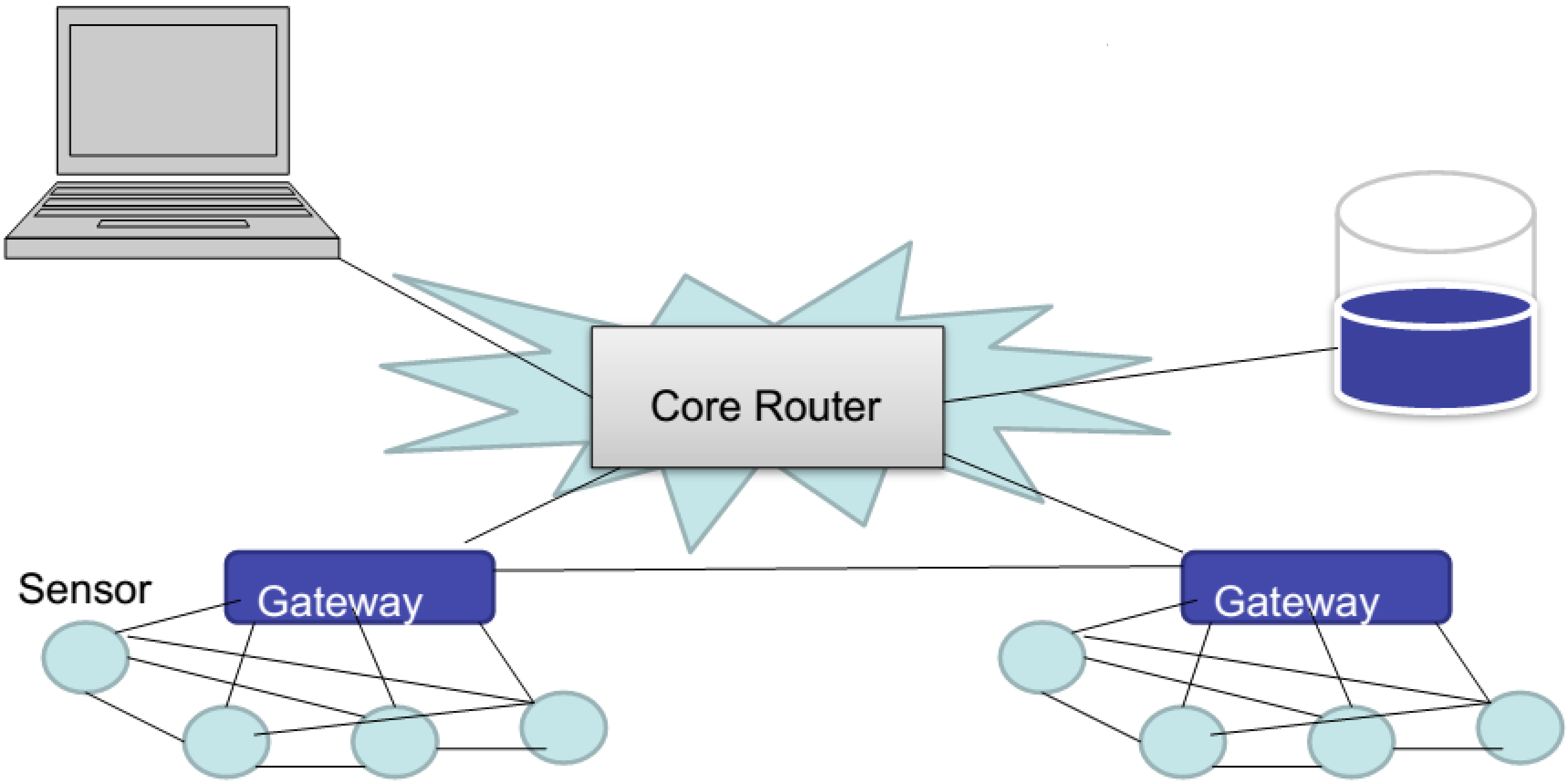
Traditional WSN



Smart Grid WSN

- Deployment topology will most likely not use a single hop to transmission gateway
- Data Processing – all data should be forwarded directly to control station
- Technology advancement in energy – less sensitive energy usage = less concern for protocols and algorithms because battery life significantly longer
- Remote maintenance and configuration
- Harsher electrical deployment environments
- Quality Of Service (QOS) for application specific WSNs becomes difficult to prioritize
- High security requirements

Smart Grid WSN



Traditional vs. Smart WSN

Traditional WSN	Smart Grid WSN
One hop transmission from gateway	Multiple sensor hops before transmission
Physical Reconfiguration of devices	Remote Reconfiguration of devices
Relay data information through routers	Data processing, QOS and delivery highly important
Secure enough to prevent information leaks (reactive)	Highly secured, (proactive) security

Wireless Security (CIA)

- Data Confidentiality – not possible to access / intercept and imitate sensor data
- Data Integrity - no unauthorized adjustment of data. Not possible to get old data or inject old data into a new network
- Data Availability - not possible to destroy communications links in WSNs, effectively making them useless. e.g. DOS attacks, jamming etc.

Other Security Threats

- Authentication and Authorization – communication among interstitial nodes must be trustworthy
- Non-repudiation –node cannot deny sending a message it has previously sent
- Threat if attacker can continue to send old messages as new data
- Forward and Backward Secrecy
  - sensor node should not be able to know any future messages once it leaves a network
  - a new joining
  - sensor should not be able to read or know previously sent messages

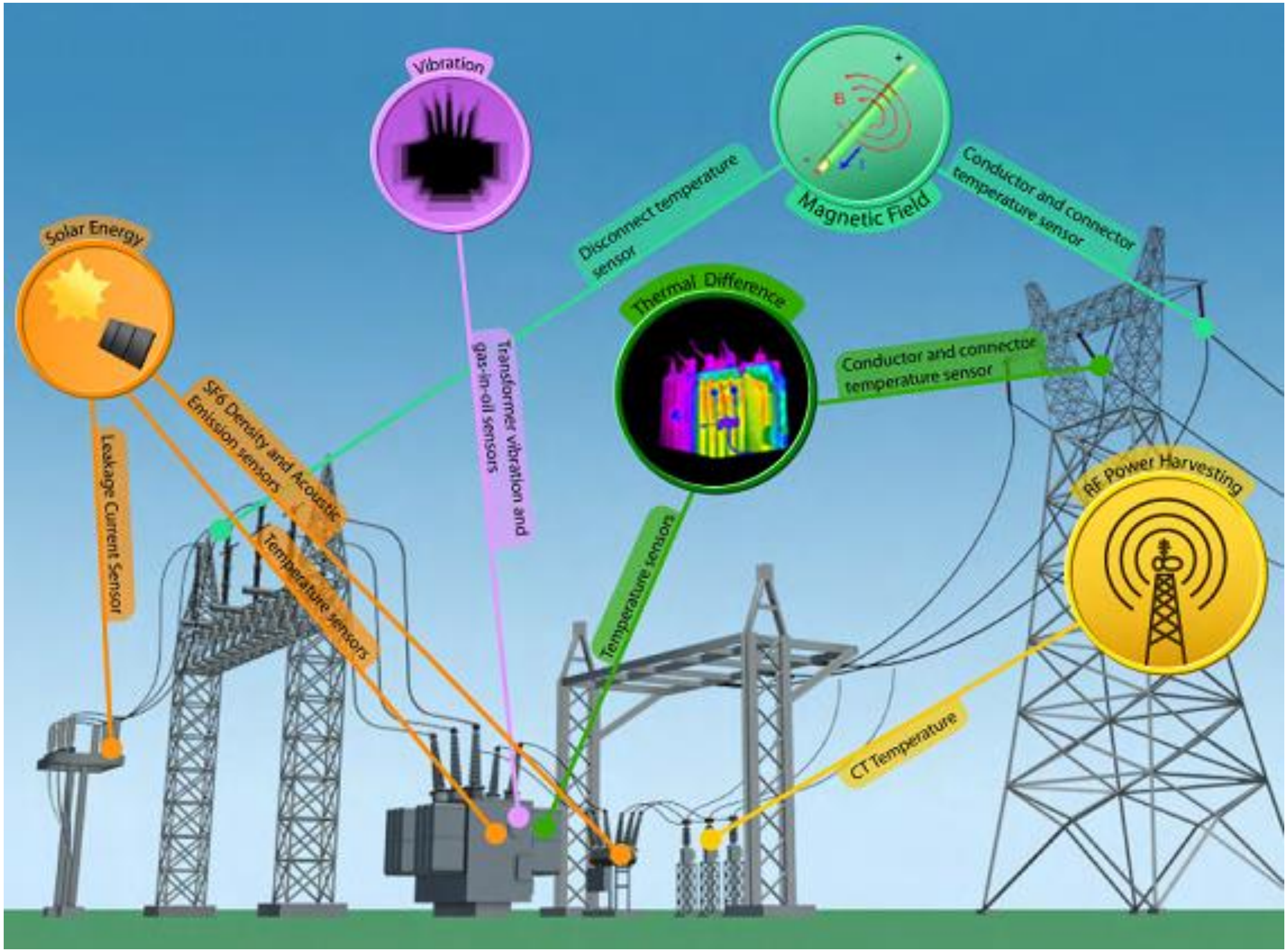
Sensor Powering

- Sensors require a power source to measure and communicate results.
- A 110/220V AC power supply is not always available – even in many substations and certainly not on transmission structures.
- Two solutions exist
  - high density non-rechargeable batteries
  - power harvesting and storage of energy from the environment

Power Harvesting Technologies

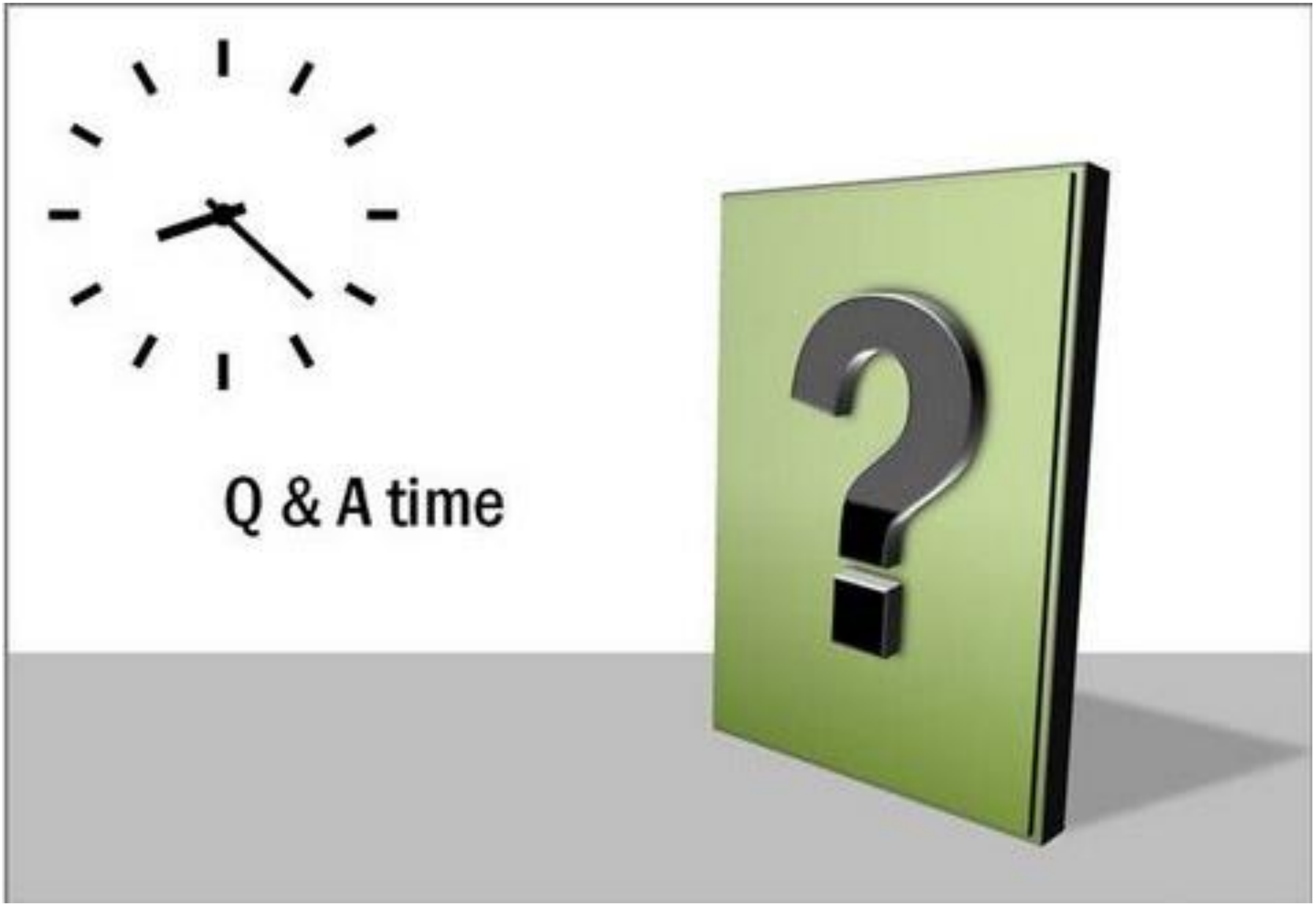
- Solar
- Vibration
- Magnetic and Electric Fields
- Thermal Differences
- Radio Frequency (RF) Energy

Power Harvesting Solutions



Algorithms and Data Visualization

- Important components for developing sensor applications relate to the need to output useful information based on the sensor data collected and the visualization of this information.
- This is achieved by first developing algorithms that relate to components condition, rating or actions, and second, by filtering out noise from results


Q & A time

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