Massively Deployed Sensors

A PSerc Tele-seminar on PSerc project T-31

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Main project elements

• **Integration of existing sensory information from sensors** (e.g. temperature and pressure, substation security perimeter status, substation battery voltage, neutral - ground voltage, liquid levels) into the EMS and alarm processing software tools.

• **Investigation of unconventional sensors** and sensory information (e.g., satellite graphic information, mechanical position and inclinometer-type sensors, static wire impedance, conduit and cable trough conductivity).

• **Development of alarm processing techniques** and algorithms that utilize a large number of sensory information sources including unconventional sensory information. The alarm processing techniques may use innovative mathematical techniques.

• The use of a **very large number of signals** for enhanced power system operation and operational decision making in order to capture new information and to enhance the accuracy, quality, and redundancy of the collected information. This includes, for example, analysis of data fusion, size and complexity of data, efficient power usage for sensors, optimal location of sensors with respect to chosen metrics, and availability of communication channels to transmit sensor data.
Forms of energy
Basis of sensory systems

- ELECTRIC
- MAGNETIC
- ATOMIC
- CHEMICAL
- POTENTIAL
- KINETIC
## Potential sensory signals

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Transmission Lines</th>
<th>Substations</th>
<th>Transformers</th>
<th>Circuit Breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Stress / Strain</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Inclination / Tilt</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Protective relay output</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
## Bandwidth requirements

<table>
<thead>
<tr>
<th>BANDWIDTH</th>
<th>POWER TRANSFORMER</th>
<th>REVENUE PT</th>
<th>RELAYING PT</th>
<th>FIELD INSTRUMENTATION APPLICATIONS PT</th>
<th>LABORATORY GRADE PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide, greater than 10 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate, 6 - 10 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate, 3 to 6 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Narrow, less than 3 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very narrow, less than 100 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assessment of the optimal number of sensors to improve an index of quality, $J$

![Graph showing the relationship between optimal cost and system order.](image)
Some innovative sensors
The Poynting vector
\[ S = [E] \times [H] \]

It may be possible to assess losses in a post type insulator by measuring the Poynting vector, \( S \), and integrating this across a surrounding surface. This is the lost active power in the insulator.
The Poynting vector

\[ S = [E] \times [H] \]
An application to the measurement of lost active power in a shunt reactor

Voltage and current are nearly 90 degrees out of phase – the low power factor is not zero due to losses
Value of a Poynting vector sensor

• Can be used to detect low level losses in systems with high levels of through power
• Can be used to detect low level losses in systems with very low power factor
• Can pinpoint location of losses – perhaps a discharge sensor
Absorption of alpha particles from an atomic source (as in a smoke alarm) can indicate the integrity of insulating oil.
Potential applications of an alpha particle sensor

• Insulating oil integrity tests
• Nondestructive testing of insulating oils
• Transformer oil signature analysis and detection – for incipient failures
A giant magnetoresistive sensor (GMR)

The basic concept is a resistance measurement which is proportional to local magnetic field – and hence transmission line conductor current.

Requires sensitive resistance measurement – e.g., via a Kelvin bridge.

Double bridge balancing.

Wide bandwidth – basically limited by the speed of the electronic bridge balancing.
Potential applications of GMR technology

- Laboratory current measurements (even at high voltage)
- Local magnetic field measurements – e.g., a hand held $B$ field instrument
- A wideband CT
Satellite image technologies

- Tree trimming prioritization
- Physical security assessment

Stereo imaging
Satellite images

• Multispectral stereo images can be obtained from satellite:
  – IKONOS, GSD = 1 m, multispectral GSD = 4 m
  – QuickBird, GSD = 0.61 m
  – OrbView, GSD = 0.41 m, multispectral GSD = 1.64 m

• The accuracy of the identification of ground objects depend on the ground sample distance (GSD) value.

• Satellite image is divided into pixels, GSD is the pixel diameter in meter

• GSD = 1 m needed for the tree height determination and GSD = 4 - 5 m are suitable for healthy vegetation identification
Software development for tree trimming prioritization using satellite images

The procedure is divided into ten steps:
1. Load a pair of multispectral stereo satellite images
2. Load the data of transmission line towers
3. Calculate the pixel location of the lines and towers on the image
4. Load the coordinates of the danger zone
5. Display the danger zone
6. Detect the healthy trees and plants within the danger zone
7. Select the threshold value for detecting vegetation
8. Calculate stereo matching for each pixel within the danger zone
9. Generate three dimensional Digital Surface Model
10. Identify high trees and plants within the danger zone endangering the line
Software development

The graphical user interface

- **Main-panel** shows a satellite image and overlays results of analysis
- **Sub-panel** displays the transmission tower as a small circle and the transmission line as a line
- **Control-panel** gives index numbers which are used to interactively identify land type such as bare land, trees, and buildings
- **Info-panel** displays a table of the list of geographical coordinates of transmission towers
Case study 1

• The figure illustrates the identification of areas with healthy vegetation

• QuickBird satellite image with a multispectral GDS = 0.61 m was used

• Location: Scottsdale, Arizona

• White points identify trees or healthy bushes from chromatic analysis
Case Study 2

- Location: San Diego, CA
- IKONOS satellite images, GSD = 1 m
- The transmission towers are located on the opposite sides of a freeway, and the lines cross the freeway
- There is a vegetation area along the right of way – along the San Diego River
- High trees depicted in white, the white oval defines the study area
Results and Case Study 2
Case Study 2

During the scanning each pixel is analyzed by calculating the normalized differenced vegetation index (NDVI) defined as,

$$NDVI = \frac{NIR - R}{NIR + R}$$

$NIR = \text{near infrared}, \ R = \text{red}$.

The effect of NDVI threshold on an IKONOS image illustrated here. The multispectral satellite image is, from top to bottom:

a) NDVI = 0.1  
b) NDVI = 0.25  
c) NDVI = 0.20  
d) NDVI = 0.25
# Case study 2

<table>
<thead>
<tr>
<th>ID</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Distance to lines (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32.759251042034705</td>
<td>117.19985426770678</td>
<td>40.78245</td>
</tr>
<tr>
<td>1</td>
<td>32.75928400942072</td>
<td>117.1998345690552</td>
<td>42.64533</td>
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<td>2</td>
<td>32.75953096171785</td>
<td>117.19973683669522</td>
<td>32.101067</td>
</tr>
<tr>
<td>3</td>
<td>32.75918758139942</td>
<td>117.19980425768894</td>
<td>38.711155</td>
</tr>
<tr>
<td>4</td>
<td>32.759336866606894</td>
<td>117.1997209176232</td>
<td>42.473488</td>
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<tr>
<td>5</td>
<td>32.759566403240605</td>
<td>117.19962773072264</td>
<td>31.185623</td>
</tr>
<tr>
<td>6</td>
<td>32.75927090915831</td>
<td>117.19960498847946</td>
<td>47.045143</td>
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<td>7</td>
<td>32.75929827272182</td>
<td>117.19955346662981</td>
<td>48.571705</td>
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<td>8</td>
<td>32.759388466048144</td>
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<td>9</td>
<td>32.759457505829374</td>
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<td>10</td>
<td>32.75943572141182</td>
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<td>11</td>
<td>32.75932871661798</td>
<td>117.19931252240548</td>
<td>24.45303</td>
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<tr>
<td>12</td>
<td>32.75923663067426</td>
<td>117.19920341145091</td>
<td>54.78344</td>
</tr>
</tbody>
</table>
Case study 2

Nearest distance from tree to line (m)

Transmission Tower

Transmission Line

Inside of Danger Zone

Healthy Vegetation

Outside of Danger Zone

15 m
Case study 2

Five closest trees to transmission lines are extracted from the tree list and marked.
## Contemplated risk and cost to benefit ratio of new sensors

<table>
<thead>
<tr>
<th>Need</th>
<th>Estimated risk</th>
<th>Estimated cost / benefit ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low cost sensors*</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Direct measurement sensors</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Increase dynamic range of PTs and CTs</td>
<td>Low - moderate</td>
<td>Favorable</td>
</tr>
<tr>
<td>Development of semiconductor sensors</td>
<td>Moderate</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Techniques using ‘non-sensors’</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Digital signal processing development for sensors</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Measurement of conductor sag</td>
<td>Low</td>
<td>Very favorable</td>
</tr>
<tr>
<td>Piezoelectric sensors</td>
<td>Moderate</td>
<td>Unknown</td>
</tr>
<tr>
<td>Very low current measurement</td>
<td>Low</td>
<td>Unknown</td>
</tr>
<tr>
<td>Transformer loss and temperature measurement</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Video applications</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Audio sensors</td>
<td>Low</td>
<td>Favorable</td>
</tr>
<tr>
<td>Double (Kelvin) bridge and other innovative bridge circuits</td>
<td>Low</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Latency – wide area measurement and control systems
Latency in delivering sensory signals

\[ T = T_s + T_b + T_p + T_r \]

\[ T_s = \frac{P_s}{D_r} \]

\[ T_p = \frac{\ell}{v} \]

\( T_s \) is the serial delay, \( T_b \) is the between packet delay, \( T_p \) is the propagation delay, \( T_r \) is the routing delay, \( P_s \) is the size of the packet (bits/packet), \( D_r \) is the data rate of the network, \( \ell \) is the length of the communication medium, and \( v \) is the velocity at which the data are sent though the communications medium (e.g., 0.6c to c, where c is the speed of light).
Latency in delivering sensory signals

It is possible to estimate the mean and variance of latency

\[ E(T) = \left[ \frac{-P_s}{D_{ro}^2} \ 1 \ 1 \right] E\left( \begin{bmatrix} D_r \\ T_p \\ T_r \end{bmatrix} \right) + T_b + \frac{2P_s}{D_{ro}} \]

\[ \sigma_T^2 = \left[ \frac{-P_s}{D_{ro}^2} \ 1 \ 1 \right] \begin{bmatrix} \sigma_{DrDr}^2 & \sigma_{DrTp}^2 & \sigma_{DrTr}^2 \\ \sigma_{TpDr}^2 & \sigma_{TpTp}^2 & \sigma_{TpTr}^2 \\ \sigma_{TrDr}^2 & \sigma_{TrTp}^2 & \sigma_{TrTr}^2 \end{bmatrix} \left[ \frac{-P_s}{D_{ro}^2} \ 1 \ 1 \right] \]
Calculation tools: the stochastic case

• These formulas are distribution free – do not depend on type of stochastic variation

\[ E(T) = \left[ \frac{1}{D_r} \right] \left[ E(P_s) \right] + T_b + T_p \]

\[ E((T - E(T))^2) = \left[ \frac{1}{D_r} \right] \left[ \frac{\sigma_{PsPs}^2}{\sigma_{TrPs}^2} \frac{\sigma_{PsTr}^2}{\sigma_{TrTr}^2} \right] \left[ \frac{1}{D_r} \right] = \sigma_T^2 \]
The WECC example

The WECC system has nearly 30,000 buses above 69 kV. It is assumed that nearly one-fifth to one-quarter of these buses are, in fact, instrumented and ultimately result in measurements. For purposes of obtaining an illustrative example, the communication infrastructure of a WACS for the WECC is postulated.

The communications system specifications used in the WECC example are shown on the next slide. The table on the next slide shows the number of measurements for each zone and the maximum and minimum delay times for each of those zones (for a measurement in each of those zones to a central location $\ell$ km away).
### Calculated delay times

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number of measurements</th>
<th>Minimum delay time (s)</th>
<th>Maximum delay time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>470</td>
<td>0.0206</td>
<td>0.0220</td>
</tr>
<tr>
<td>Zone 2</td>
<td>907</td>
<td>0.0206</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 3</td>
<td>1310</td>
<td>0.0208</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 4</td>
<td>840</td>
<td>0.0207</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 5</td>
<td>504</td>
<td>0.0207</td>
<td>0.0220</td>
</tr>
<tr>
<td>Zone 6</td>
<td>638</td>
<td>0.0207</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 7</td>
<td>1176</td>
<td>0.0219</td>
<td>0.0222</td>
</tr>
<tr>
<td>Zone 8</td>
<td>1008</td>
<td>0.0207</td>
<td>0.0220</td>
</tr>
</tbody>
</table>
Implications of latency – WECC example

In order to assess the impact of latency, the same WECC example is reconsidered with PSS measurements and controls implemented.
Impact of 0.1 s delay

Remote input delayed by 0.1s
Remote input included without delay

Generator electrical power output (pu on machine MVA base) at local bus

Impact of 0.1 s delay
Impact of 0.5 s delay

Generator electrical power output (pu on machine MVA base) at local bus

- Remote input delayed by 0.5s
- Remote input included without delay
Impact of latency

- **Increases settling time** (graph at the right is the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping)
- There are cases in which latency in PSS signals result in instability
- Long latency times (e.g., > 0.25 s) show the greatest number of problematic cases
Impact of latency

- The latency issue is worse for cases of transmission circuit outages.
- For example: the impact of delaying the remote bus frequency input from bus 35 to the PSS at bus 4 on interarea damping with a double circuit outage.
Main conclusions from the latency study

• A straightforward calculation method and model of communication delays in power system WACS are shown for the case of dedicated sensory communication channels.

• Utilizing data representative of the WECC system, for a 50 Mbps network, an approximate interarea time delay of 20.6 ms is found.

• The standard deviation of the total interarea delay time may be calculated as well – and a typical value is about 4.6 ms.

• The latency calculations have been applied to a WACS test case. Introducing a remote input to a single PSS has been shown to enhance the stability of the test case by increasing the damping of the interarea mode under study. Latency has the effect of reducing the effectiveness of controls. However, WACS, with its attendant latency, appears to be more effective than local control in damping interarea oscillations.

• If additional processing delays were to exist, especially of the order of those introduced by satellite based communication, conditions of underdamping will need to be checked carefully.
Some concluding remarks on the massive use of sensors in power systems
Advantages of deployment of sensors

1. **Advanced warning** of developing problems resulting in a fewer catastrophic failures.

2. **More efficient operations** of equipment and overall system resulting in lower losses, better conservation of resources and optimum operation.

3. **Improved emergency response** to problems; operators will have more information to diagnose and deal with problems for both normal and emergency operations.

4. **Increased security** of power grid, thereby, enhancing the homeland security.
Examples of innovative sensory technology

- Poynting vector (an electromagnetic combination of electric and magnetic field) instrumentation may offer the capability of measurement of low electric and magnetic fields. The main issues to be addressed are the shielding of the sensor to reveal specific components of the Poynting vector. The instrumentation of the Poynting vector for electric power applications is a high risk venture.
- Measurement of atomic particle absorption (e.g., for detection of transformer oil contamination)
- Utilization of satellite electromagnetic (e.g. GPS) methods for sag identification of overhead transmission circuits, processing of satellite images for tree trimming prioritization
- Use of time stamped remote measurements for PSS signals
Questions – Comments – Remarks