Application of Sensor Networks for Secure Electric Energy Infrastructure

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Outline

- Introduction
- Mechanical characteristics of overhead transmission lines
- Wireless mechanical sensor network
- Implementation and simulation results
Introduction

- Increasing threats of terrorism around the world, along with extreme natural events, bring attention to the security of electric transmission infrastructure.

- Current method to assess the damage on the transmission grid is by visual inspection.

- For transmission lines dispersed over hundreds of miles, visual inspection is difficult.
Introduction

- Traditionally, the operator in the control centre only receives indication that an electrical fault occurred without any knowledge of whether it is temporary or permanent.

- Decide the condition of the event by reinsert the faulted line.

- Recent blackouts in US and Italy have shown that failure to assess and understand the condition and delay to act can make a single outage into widespread blackouts.
Introduction

- Utilization of wireless sensor network to detect mechanical failures in transmission lines.

- Sensors are installed in predetermined towers and communicating via wireless network.
Introduction

• Objective:

• Obtain a complete physical and electrical picture of the power system in real-time

• Diagnose imminent and permanent faults

• Determine appropriate control measures that could be automatically taken

• Suggest to the system operators once an extreme mechanical condition appears in a transmission line.
Mechanical Characteristics of Overhead Transmission Lines
Transmission Line Components

- Foundations
- Supports
- Interfaces
- Conductors
Supports

- Strain supports (angle-strain)
  - carry conductor tensile forces in the direction of conductor

- Suspension supports
  - carry conductors in a straight vertical position
Mechanical Loads on Structures

- Environment
  - wind, ice, snow, earthquakes, flood
- Human related hazards
  - accidents, terrorism
Wind Induced Conductor Motion

- Three categories (different in frequency, amplitudes and effects on conductors, interfaces and supports)

- Aeolian vibration - small amplitude, relatively high frequency

- Conductor gallop - vertical low frequency, high amplitude

- Wake induced oscillation - twist of bundled conductors
Effects of Snow and Ice

- Increase the tensile forces of the wires due to added weight
- Change their aerodynamic characteristics by changing the shape of the surface exposed to the wind
Effects of human related hazards

- Accidental or malicious event involves disturbance on the mechanical structure. Thus, this can be detected by the same sensors aimed at monitoring wind and ice.

- Impact of bombing goes from collapse of the entire structure to limited damage.

- Explosive blast causes vibration, sometimes even tilt of the tower.
Temperature Concerns

• Current can cause temperature rise.

• Hot spots appear in the coupling between energized conductors and their interfaces.

• Hot spots can produce a thermal runaway effect that will degrade the mechanical reliability of conductors and lead to catastrophic failure.

• Need to reduce the current flowing through the line once a hot spot appears.
Wireless Mechanical Sensor Network
Sensor Selection

- Tension (strain) sensor
- Displacement sensor
- Acceleration sensor
- Temperature sensor

Table I. Sensor application matrix

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tension/Strain</th>
<th>Vibration</th>
<th>Tilt</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Conditions</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Ice Accretion - Low Wind</td>
<td>Increased, inside</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Medium - High Wind - Bare Conductor</td>
<td>Increased, inside</td>
<td>High Frequency Inside Limits</td>
<td>Normal Values</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Medium - High Wind - Uniform Ice</td>
<td>Increased, inside</td>
<td>High Frequency Inside Limits</td>
<td>Normal Values</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Galloping</td>
<td>Increased, at Limit values</td>
<td>Low Frequency High Amplitude</td>
<td>Oscillating Values</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Explosion Blast</td>
<td>Sharp Increase</td>
<td>Sharp Amplitude Increase</td>
<td>Oscillating Values</td>
<td>Temporary rise</td>
</tr>
<tr>
<td>Compromised Structure - Uniform</td>
<td>Increased in strain supports</td>
<td>Loss of equilibrium in suspension supports</td>
<td>Apreciable Tilt 0-90 degrees</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Collapsed Structure</td>
<td>Sharp Increase, then goes to zero</td>
<td>No Information</td>
<td>Apreciable Tilt ~ 90 degrees</td>
<td>Normal Values</td>
</tr>
<tr>
<td>Hot Spots</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Uniform between conductors and nearby supports</td>
</tr>
<tr>
<td>Overheating</td>
<td>Increased strain caused by sagging</td>
<td>Normal Values</td>
<td>Normal Values</td>
<td>Isolated high temperature</td>
</tr>
</tbody>
</table>

Given that temperature is also important to maintain the appropriate level of observability for earthquakes and wind conditions, it is proposed to use a set of sensors based in that application, where researchers have found that tension or stress can be measured using tension or strain transducers close to all the points of attachment of conductors. For a more complete assessment of the mechanical variables on the line, it is recommended to measure tensile forces at the attachment point of conductors to detect possible hot spots, which can be optimized given that heating conditions are highly localized. For the recommended implementation of a wireless mechanical sensor network, it is proposed to use a set of sensors with particular characteristics and placement, as shown in the Table I.
Sensor Placement

- Tension (strain) sensor: at the interface of the strain supports, on both sides at the attachment of suspension supports on every third tower
- Accelerometers (vibration and tilt): in the support body and conductor attachment points
- Temperature sensor: at the attachment points of conductors
It is proposed to rely on wireless communication between towers, since they would offer a reliable transmission path in the event of a failure of a support structure, provided that the causal event does not damage the transmitter (as in the case of an explosion caused by an act of sabotage).

The inherent lineal characteristic of a transmission line drives the overall topology of the sensor network. Communications between nodes in such a topology are reduced to their adjacent node and at most two hops ahead (communications range permitting). Thus, for messages originating from a node in the middle of the line to reach the substation, they should be relayed through all the intermediate nodes.

The construction characteristics of transmission lines, with supports separated hundreds or even thousands of feet between each other pose a hard constraint for the range requirement for wireless communications between sensor nodes localized on different structures. By design, the communications range of smart sensors is not very long and extending it is not efficient due to power supply limitations [15]-[17].

A two layers model is proposed to overcome the restrictions imposed by the range/energy management issue on the sensor nodes as shown in Fig. 2. The sensor nodes installed in each structure form a local sensor group (LSG) with required communication ranges not greater than 100 feet given the dimensions of typical transmission line supports. A local data and communications processor (LDCP) installed at each support is used to aggregate the information from the LSG. Its radio can achieve a larger range and count with an increased communications bandwidth due to the fact that it does not have size and power constraints. For that matter, it can harvest power from an inductive source placed near the closest phase conductor and can also count with a bigger rechargeable battery. The normal range expected for the application varies from 300 to 1500 feet, using more powerful radios in particular structures where longer spans exist.

Sensor data on every LSG is aggregated and analyzed for verification purposes on the LDCP. Data verification is possible thanks to the inherent relation between the sensed variables, as was discussed previously. Sensors on the LSG and their corresponding LDCP will form the Layer 1 of the WMSN.

The interaction between the LDCPs on each support is the basis for the Layer 2 of the WMSN and forms the inter-support communications and collaboration (ISCC) Layer. This layer handles all the message processing and transmission required for delivering the mechanical status information to the substation.

In this paper, a method is proposed to enable collaboration between LDCPs in adjacent supports as well as data collection from all the LDCPs in a transmission line that involves sequential message broadcasting across the line. For executing both functions, two modes of operation (Partial mode and...
Distance among two adjacent towers is typically hundreds to thousands feet. Thus, it’s difficult for sensors to transmit data to another tower.

Two layers model:

Layer 1: a local sensor group (LSG, transmission range 100 feet) + a local data and communications processor (LDCP) for data verification

Layer 2: interaction between LDCPs on each supports to deliver data to substations.
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Figure 1. Overview of the proposed sensor placement.
Data Collection Process

- A local substation processor (LSP) located at one end of transmission line initiates the data collection sweep.

- Directionality is achieved by including sender and receiver address in the header.

- The process continues until the message reaches LSP at the other end of the transmission line.

- The other LSP triggers a data collection sweep in the opposite direction.
Data Collection Process

- Two modes: partial mode and full mode

- Partial mode: message only contains maximum value of each variable group (vibration, strain, temperature) and corresponding sensors’ location.

- Full mode: collects the status from all the sensors in the transmission line, enabling LSP to obtain a complete picture.
Time Response

- Common response times for clearing faults in electrical systems are in order of 50 to 100 ms.
- Impossible for message to reach substation in WMSN within this response time, even in partial mode.
- WMSN cannot be used to provide principal or backup protective functionality.
- One possible application for WMSN is SCADA system.
- SCADA collects information from substations every 4s. There is enough time for a full mode sweep and several partial mode sweep.
Implementation and Simulation Results
A power grid

The integrated operation of the IPSS software, AREVA's DTS and the WMSN concept was tested on the EMP60 power system model (Fig. 4), assuming that a wireless mechanical sensor network is installed in the line Martdale – Ceylon 345 kV for monitoring its mechanical health.

The following simulations model different mechanical failure modes in the monitored line and their associated dynamics. The objective of the test is to verify the appropriate response and recommendations provided by the IPSS software as the power system is simulated in the dispatcher training simulator.

Figs. 5 and 6 show the evolution of the system without WMSN after the outage of the line Martdale – Ceylon and the consequent overload of Chenaux – Picton. It can be seen that if during the time spent for reclosing the line, an additional outage occurs in Chenaux – Picton due to its overloaded condition, the system experiences a voltage collapse as shown in Fig. 6.

Sensors installed in this line

Assuming the presence of the WMSN monitoring the line Martdale – Ceylon, a simulated imminent failure mode will trigger the IPSS to recommend generation shift actions before the actual outage of the monitored line as shown in Table II.

Table II. Generation shift recommendations

<table>
<thead>
<tr>
<th>Plant</th>
<th>Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanticoke</td>
<td>- 80 MW</td>
</tr>
<tr>
<td>Chenaux</td>
<td>- 85 MW</td>
</tr>
<tr>
<td>Lakeview</td>
<td>+ 67 MW</td>
</tr>
<tr>
<td>Douglas</td>
<td>+ 98 MW</td>
</tr>
</tbody>
</table>

With the reduction of the line flow as a result of the recommended actions by the IPSS, the line Chenaux – Picton will achieve 100% loading (700 MW) after the outage of Martdale – Ceylon (Fig. 7).
Simulation Results

Consequence of the outage on the line Martdale-Ceylon without WMSN
Simulation Results

- With WMSN deployed on the line Martdale-Ceylon, with a progressively deteriorating mechanical condition
Simulation Results

* With WMSN deployed on the line Martdale-Ceylon, with a sudden outage on Martdale-Ceylon
Thank you!