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Vibration Monitoring of Power Distribution Poles

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VIBRATION MONITORING OF POWER DISTRIBUTION POLES

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Abstract

Some of the most visible and least monitored elements of our national security infrastructure are the poles and towers used for the distribution of our nation's electrical power. Issues surrounding these elements within the United States include safety such as unauthorized climbing and access, vandalism such as nut/bolt removal or destructive small arms fire, and major vandalism such as the downing of power poles and towers by the cutting of the poles with a chainsaw or torches. The Idaho National Laboratory (INL) has an ongoing research program working to develop inexpensive and sensitive sensor platforms for the monitoring and characterization of damage to the power distribution infrastructure. This presentation covers the results from the instrumentation of a variety of power poles and wires with geophone assemblies and the recording of vibration data when power poles were subjected to a variety of stimuli. Initial results indicate that, for the majority of attacks against power poles, the resulting signal can be seen not only on the targeted pole but on sensors several poles away in the distribution network and a distributed sensor system can be used to monitor remote and critical structures.

Introduction

The energy infrastructure is one of several critical targets for terrorists that, when disrupted, can cause major economic, safety, and physical damage to the public health and well being. Power transmission lines are particularly vulnerable since many cross miles of remote country through dedicated corridors with no effective means for physical security detection or protection. Recent events have shown that these systems are targets of attack in the United States and around the World (Figure 1). Successfully coordinated attacks on major transmission structures could bring down entire regional grid power supplies, similar to that experienced during the August 14th, 2003 blackout in the Northeastern United States. High voltage transmission lines and associated structures are also time consuming to repair or replace and damage and associated outages cost millions, possibly billions, of dollars in lost revenue, not to mention the effect on public safety and the impact on the psyche of a large population segment.

The ability to alert local and regional utility operators of pending attacks in real time may provide sufficient warning to take preemptive system control, to prevent regional outages, and allow law enforcement agencies the opportunity to capture perpetrators in the attack area. Currently technology or physical surveillance devices exist that can perform this task (i.e. Surveillance cameras, roving guards, intrusion detection systems), but these are impractical due to the high cost of implementation, maintenance, and operation.

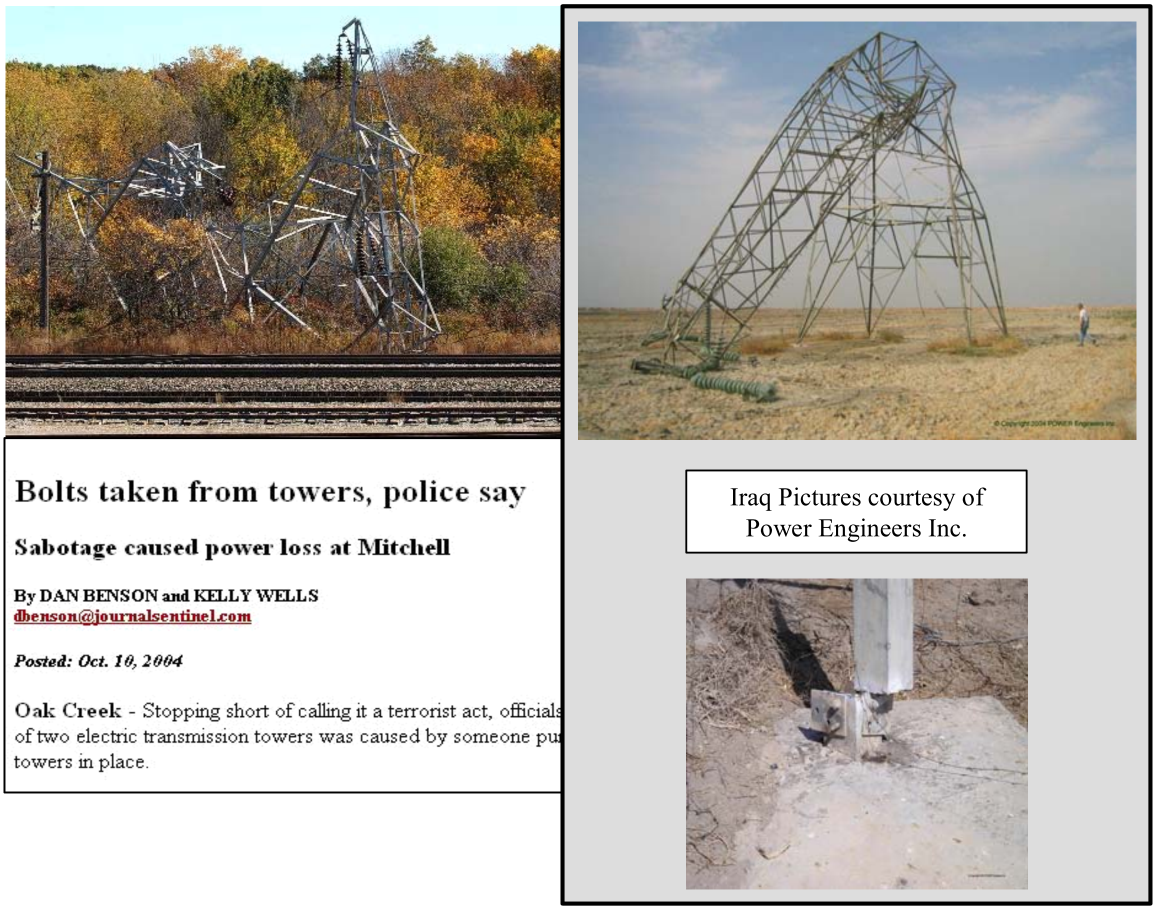

Figure 1: Images from recent transmission tower attacks. The image on the left is from news reporting on two towers that were downed in Oak Creek Wisconsin on October 9, 2004. These towers collapsed after having the bolts removed at the base of the towers. More extensive damage occurred to distribution networks in Iraq (images on right) when towers were toppled and destroyed to get at the transmission cables for the recyclable metals.

To address the need for securing the national transmission infrastructure, the INL set out designing an inexpensive, easy to install, and minimal maintenance technology for identifying and communicating impending or in-progress attacks on power transmission line structures (loosening mounting bolts, cutting mounting points, shooting insulators). The goal is to design a communications network of small inexpensive and low power electronic sensor platforms that mount on the conductors of an electric power transmission or distribution system. These sensors have the ability to communicate with each other and to pass communications to a monitoring station at the end of the line. Currently the platform has the ability to measure conductor borne vibrations, sense infrared (IR) movement, and measure conductor temperature. It derives its required power inductively from the transmission line and has the ability to store energy when the line power is interrupted.

While sensor development has been the primary goal in the last two years, geophysicists at the INL have been tapped to provide information concerning the signals expected from tampering. In preparation to the design of algorithms used in the detection and discrimination of vibrations associated with tampering, a base dataset was collected to test signal transmission distances and characteristics. This initial data set was collected for a variety of active sources including a pendulum weight drop (to simulate impact sources such as small arms fire), the hand removal of a tower base support nut, a hand saw, and a battery powered circular saw. Data was collected with a 48 Channel Geometrics Geode system and 14 Hz geophones placed in simple three component assemblies and attached to transmission structures (poles and un-energized cables). Initial processing of the data shows extremely good coupling between towers and most sources have easily recognizable vibrations signals that are distinctly recognizable over a span of several poles

Data Collection

Vibration data was collected at the Idaho Falls Power Company vehicle yard on transmission poles overlooking the power station's turbine outflow into the Snake River. Two Poles were instrumented each with three three-component geophone assemblies, one at the bottom middle and top of the pole. The instrumented metal pole was designated Pole 0 and is part of the transmission path connected to neighboring poles by three tensioned load bearing cables. A nearby wooden pole designated Pole 0A connects to Pole 0 with a single un-tensioned ground wire near the tops of the poles.

Source poles included the instrumented poles (Poles 0 and 0A), and a series of poles across the Snake River that are progressively further along the transmission route. These poles were designated Pole 1 – Pole 3, metal poles identical to pole 0, and Pole 4, an older wooden pole (Figure 2). Metal poles were used for pendulum weight drop and nut removal tests while the wooden poles were used for pendulum weight drop and saw tests. Pendulum weight drop tests and nut tests were applied directly to the poles while the saw test was performed on a sacrificial piece of wood tightly strapped to the wooden poles.

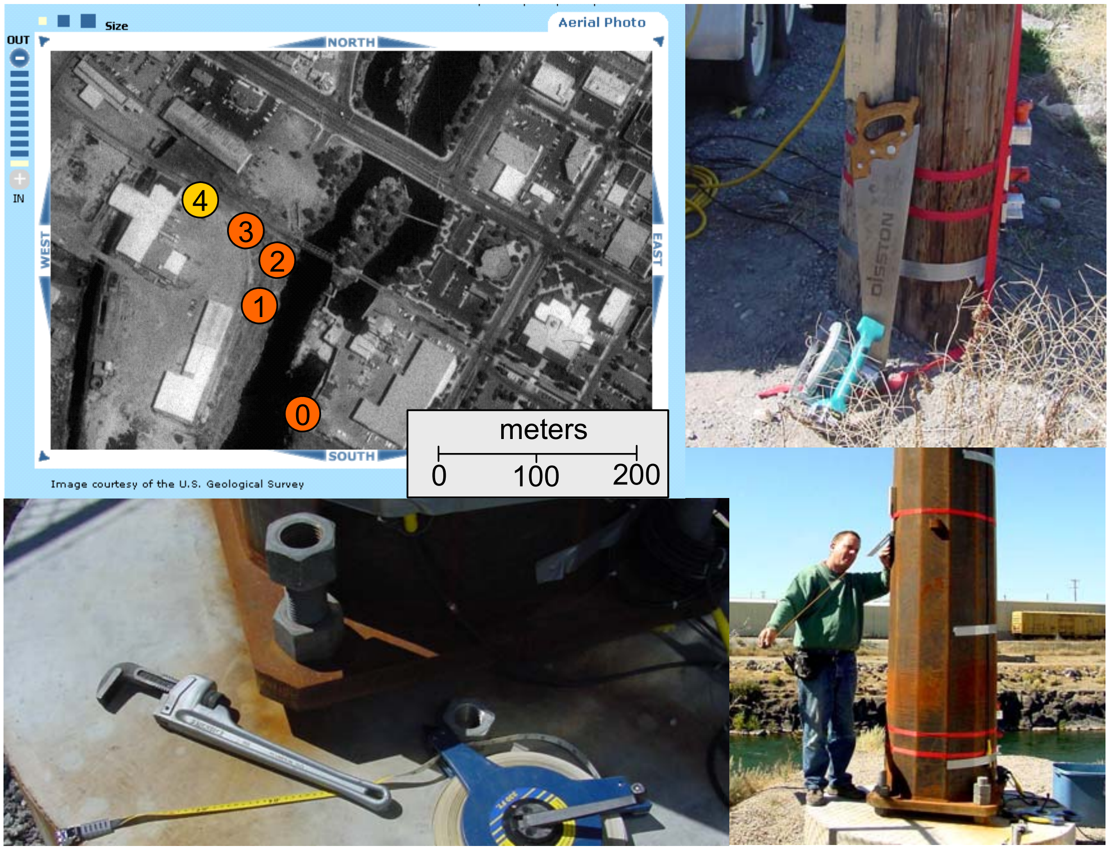

Figure 2: Images from the Idaho Falls Power Station test. The aerial photograph shows the area around the Idaho Falls Power Station. The small numbered dots indicate the locations of the power poles (orange – metal, yellow – wooden) used for this study. A second wooden pole designated Pole 0A was 6 meters from Pole 0 and connected to it with an un-tensioned ground wire only. Both Pole 0 and Pole 0A were instrumented with three simple three-component 14 Hz geophone assemblies physically strapped to the poles. Various sources were applied to Poles 0 through 4 and resulting signals recorded on poles 0 and 0A. These sources are shown and include a 1 meter pendulum weight drop being applied to Pole 0 (lower right), manual and powered saws shown at the base of Pole 0A (upper right), and the manual twisting of a pole base support nut as shown at the base of Pole 0 (lower left).

Data collection parameters depended on source type and fell under either a manually triggered single four-second file, collected at 4 KHz sampling, for impact tests (weight drop). Or as continuous two-second files (8 KHz sampling) for longer duration events (nut and saw tests). No accurate timed trigger was available for the experiment so evaluation of travel time from the impact tests can not be performed though visual observation at the time of recording tended to indicate a near instantaneous arrival, probably dependent on the high sound velocity in the tensioned metal cables.

Results

Data has been preprocessed and grouped for visualization within several programs including ProMAX and in-house signal processing and imaging software developed in the Matlab and LabView environments. Figure 3 shows data from the Idaho Falls Power Station experiment including the weight drop, nut and saw tests.

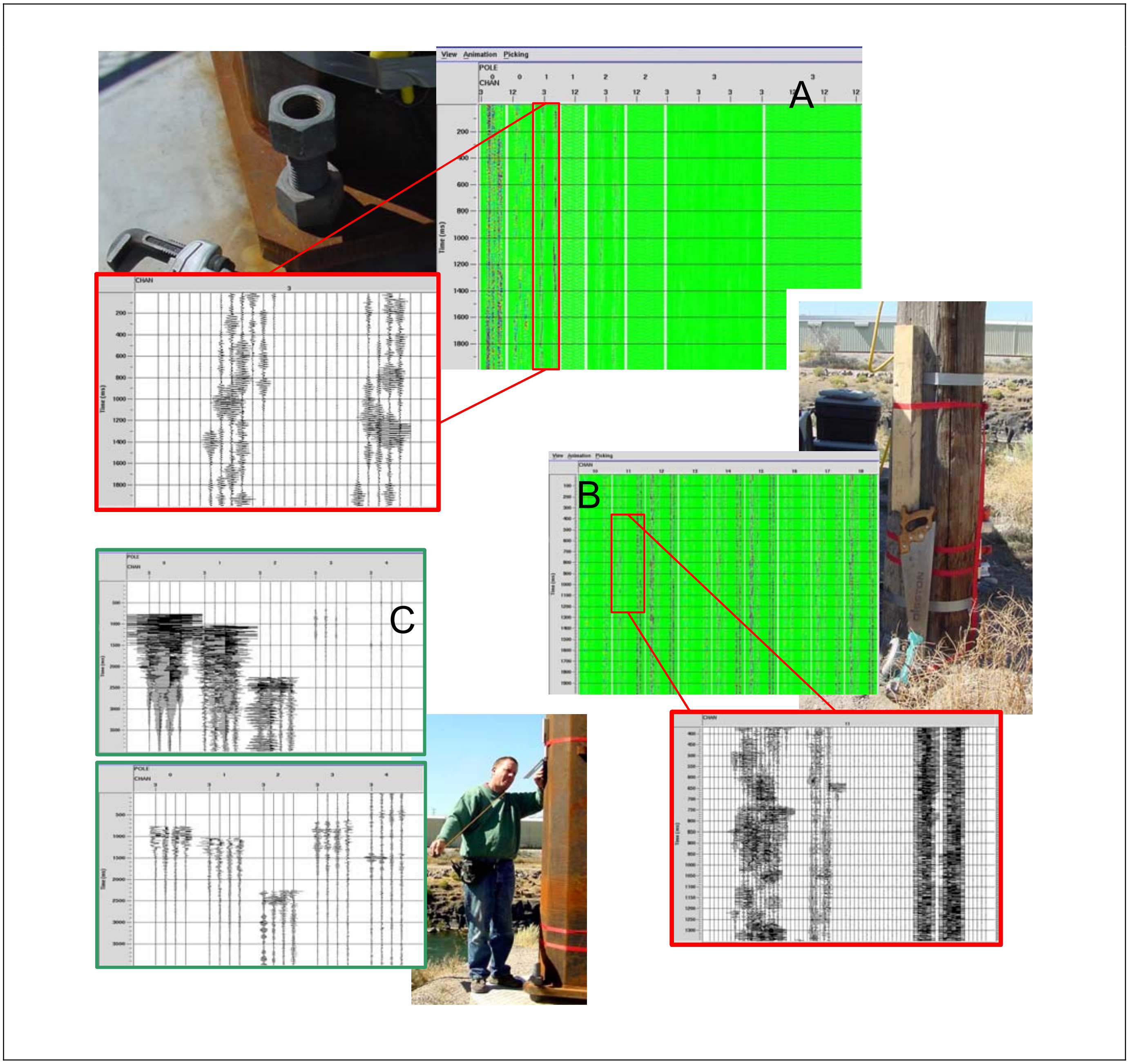

Figure 3: Data from different sources plotted by source pole. The upper left group, labeled as 'A', shows the signal arriving at the top of pole 0 (Channel 3) and 0A (Channel 12) when nuts are hand twisted on and off at the base of poles 0 through 3. The green plots show amplitude content over the roughly one minute recording period. In these plots the two second long consecutive traces collected in continuous mode are plotted next to each other to show the time history of the tests. The arriving energy associated with manipulating a nut on these towers is clearly defined several poles away. The attached wiggle trace gives a better view of the nature of these signals. Group B shows data from the saw tests on Pole 0A. These data clearly show the difference between the signal from a hand saw (early in the record) and the uniform signal from the power saw (later in the test). Group C shows the results from impact tests. The upper plot shows traces scaled to a normalized value so relative amplitude between source poles is observable. The lower plot shows traces individually equalized so the arrivals from the further poles area apparent. Due to the lack of an available triggering mechanism for these tests, arrival times cannot be used for any interpretive purposes.

Nut Manipulation Tests

The nut manipulation tests started with the beginning of continuous data acquisition on the Geode system (two second records at 8 KHz). After waiting several seconds a nut was manually twisted onto the exposed bolt at the base of the tower. Once the nut was on, another pause of several seconds preceded the removal of the nut. Then several seconds passed before the data collection was terminated. This procure produced the banded amplitude plot shown in Figure 3 (A). The test showed signal energy clearly from out to Pole 2. Little is seen from Pole 3 though more advanced processing may show a subtle signal above the background energy levels (noise).

Saw Tests

Saw tests were performed on Poles 0A and Pole 4 with the same data collection methodology as the nut tests. The results show a distinct difference between the signals from a hand saw and a power saw with the power saw data showing greater uniformity in the recorded signals. Amplitude vs. distance analysis could not be performed on this data as only two poles were available. The data in Figure 3 shows results from geophones on Pole 0A as the saws were applied to that pole. Clearly the data shows strong signals on the affected pole but the nearby pole (Pole 0) showed little signal from the saw test was transferred through the un-tensioned ground wire that connected them. Some energy from the saw tests on the distant Pole 4 did show up on the Pole 0 sensors, but the signal amplitudes were barely above the noise.

Weight Drop Tests

Weight drop test were performed to simulate impacts to the structures such as from rifles, rocks and hammers. Data was collected by starting a four second (4 KHz sampling) and immediately signaling by radio to the person dropping the weight. This method collected the full waveform of the test but did not allow for a well defined zero trigger time. The source included two different weights dropped from different angles to test the linearity of energy transfer between poles. During these tests, the high coupling inherent in the system became apparent as signals were observed just from the process off lightly touching the angle measuring device (plastic protractor) to the pole prior to the weight release. Results from a standard weight release, by pole, are shown in Figure 3 (group C). The upper plot shows the traces scaled to a common normalized value so relative amplitude from each pole can be assessed. This shows good coupling out to Pole 2 but greater energy loss after turning the corner in the transmission path (Poles 3 and 4). While the energy level drops, the lower plot (individual trace scaling) shows the signal is still recognizable above the background noise even with the lower energy levels.

Continuing Efforts

Obviously a fair amount of processing still needs to be performed on the data set collected at the Idaho Falls Power Station. In this last year the major effort has been put into developing the sensor that was deployed in recent tests alongside the Geode seismic system (Figure 4). This effort culminated in a field test at an INL power test bed location and in a high voltage coronal discharge test of the sensor package. Future needs include processing of both data sets with the goal of developing signature signal sets for a variety of tampering, to test linearity, to build structural transfer functions, and for further development of the autonomous sensor to increase sensitivities.

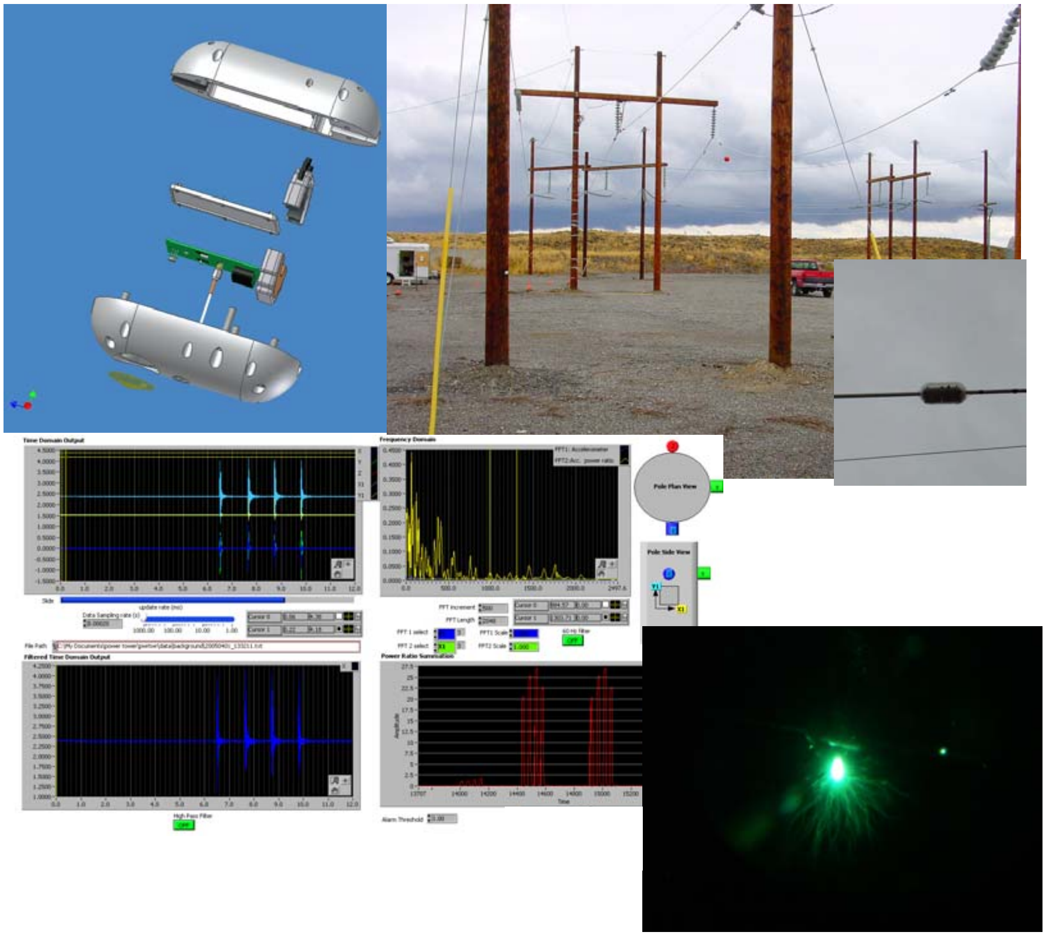

Figure 4: Images from recent work including an exploded drawing of the current sensor and it's deployment to several test facilities including an INL test bed (above) where experiments combining the sensor output and data from the seismic system were performed. Data is currently waiting to be processed for this experiment. The lower data plots show results from the accelerometers mounted in the sensor to impact tests on a nearby pole. Finally the sensor was put through testing for coronal discharge at high voltages (320 kV). Results from the coronal test indicate some re-engineering of the sensor is required prior to deployment.

Conclusions

One of the most visible and least monitored elements of our national security infrastructure are the poles and towers distributing our nation's power. This paper detailed some of the geophysical efforts being employed to support research in developing inexpensive and sensitive sensor platforms for the monitoring and characterization of damage to the power distribution infrastructure. A simple application of a seismic system was used to collect some supporting data and for comparison with the sensor platform being developed. Signals from a variety of sources including pendulum weight drop, manual nut manipulation and saws, applied to existing poles, indicate coupling between poles is very high and signals associated with the common methods of vandalism can clearly be seen several poles away. Work continues to define the pole transfer functions and the ground to pole transfer functions needed to develop accurate alarms.

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