Evolution of Real-time Monitoring and its Future Benefits

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Abstract— Transmission lines were being monitored for ice loads by a utility in the U.S. in real time in the late 1930s. Since that time both custom and commercially available systems for real time monitoring of ice and wind loads as well as sag, current, conductor surface temperature and other parameters have been developed and deployed. Structural health monitoring is also being performed in real time for machinery, buildings, bridges and other structures. New sensors, power supplies and communications systems are being developed for many different applications that may also have application in the real time measurements for ice and wind loads on lines and the weather that produces them. This paper describes the evolution of real time monitoring of transmission lines. Currently available instrument systems for transmission lines are also reviewed. Some of the new technologies being developed and applied in other industries are described. The future benefits of real-time instrumentation with a particular emphasis on snow, ice and wind are discussed.

I. Introduction

Real time monitoring of transmission lines began as early as the 1930s and gained momentum in the middle of the 20th century. Marketing of commercial systems began in earnest in the 1980s. In the same time frame, a number of transmission line test sites for wind and ice loads were installed by utilities and utility research organizations around the world. In the last decade commercialization of new real time monitoring systems has been proceeding rapidly. At the same time, structural health monitoring (in real time) of aircraft, motor vehicles, bridges, and other civil infrastructure has been growing by leaps and bounds; early detection of problems and improved scheduling of maintenance are the main driving forces.

II. Pioneering Efforts

Thomas Edison invented the first practical incandescent light bulb in 1879 [see 1, for this early history]. The Pearl Street Station, the first commercial central power plant, began operation using direct current in September 1882. The first AC system was installed in the United States in 1886 in Great Barrington, Massachusetts.

In 1891, a demonstration of the feasibility of long distance high voltage transmission of power was made in Germany. A 25-kV three phase AC transmission line was built between Lauffen and Frankfurt, a distance of 175 km (109 mi). Progress in high voltage AC transmission systems was rapid, driven by the desire to bring power from hydroelectric generating stations to distant population centers.

In 1914 there were 55 lines worldwide with voltages of 70 kV and above [2, as shown in 1]. By this time, awareness of the seriousness of ice loads and the operational problems they caused was also clear. Reference [3] recommended design for 12.5 mm (½ in) of ice with a factor of safety of 2 on the conductor tensile strength (this recommendation was later incorporated into the U.S. National Electrical Safety Code). An AIEE (American Institute of Electrical Engineers) sub-committee report recommended designing for 19 mm (¾ in) of ice in some areas of the U.S. [4].

Physical tests of the effects of ice on lines were also performed in the same time period [5, 6]; these tests resulted in horizontal offsetting of the conductor attachment points on double circuit towers.

Utilities were also working on methods of removing ice, principally by increasing the current through lines to melt the ice using the joule effect.

The American Gas and Electric Co. installed the first of nine ice ("sleet") detection systems on their 132 kV transmission lines in the U.S. states of Ohio and Indiana in 1938 [7]. The detectors were based on measurements of the current transmission by their power line carrier system. Power line carrier systems impress a high frequency signal on the conductors of a transmission line. These signals are primarily used for the control of relays to operate circuit breakers. After observing that the signal strength was attenuated by ice accreting on the lines, they developed circuits that were added to the system to give them a measure of the amount of ice accumulating on the lines. This information was then used to schedule ice melting.

The Bonneville Power Administration (BPA) service area is in the northwestern U.S. BPA has a number of transmission lines that cross passes in the Cascade Mountains where severe icing occurs. Beginning in 1952, BPA began installing dynamometers with maximum load indicating follower needles in both dead-end and suspension insulator strings ten energized lines and three non-energized test spans [8, 9]. In 1957, telemetry equipment was installed to transmit data from load cells in two lines in Stephens Pass. This provided real time monitoring of the ice loads on the line [10]. Fig. 1 shows a block diagram of the system.

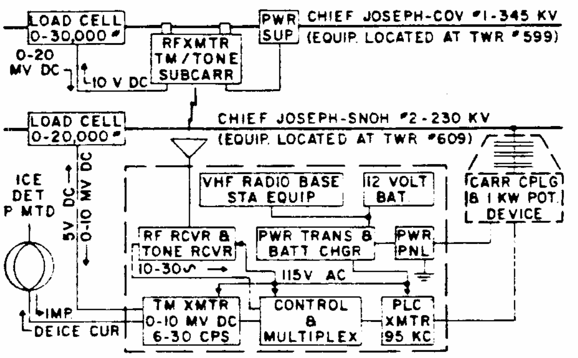

Fig. 1. Block Diagram of BPA Ice Load Telemetry System [10]

The value of the telemetry system was demonstrated during an ice storm in November 1963 in which the tension in the conductor of the 230 kV line reached 70% of the maximum design load, with the 345 kV line reaching 147% of its maximum design load.

An experimental ice detector was also constructed of perpendicular circular loops of conductor; however, the weight of ice formed on the ice detector and the weight of ice on the lines did not correlate well.

III. Instrument Sites

The following paragraphs describe both operating transmission lines and test spans with instrumentation for monitoring ice loads. This may not represent all of the current and past ice monitoring locations. It is based mainly on a review of previous IWAIS Proceedings.

A. Belgium

Reference [11] includes a brief description of a test line in Belgium for testing anti-galloping devices.

B. Canada

1) Ontario

In 1975, Ontario Hydro began monitoring ice loads on their Orangeville 115 kV line [12]. Instrumentation was added to four more lines in the next six years. The conductor load and insulator inclination (in two directions) was measured with a commercial load cell and a custom tower attachment that included two rotary transducers. Strain gauges were used to measure forces in tower members. Foundation displacements were also monitored using linear displacement transducers. Data acquisition and storage were done on site with data stored on magnetic tape.

Ontario Hydro established a test site in Ottawa in 1989 [13]. This site included a load cell and 2-axis rotary transducers as shown in Fig. 2.

The site also included a conventional anemometer, an ice-free anemometer, a heated tipping bucket rain gauge, temperature sensors, and a probe to measure droplet size and liquid water content.

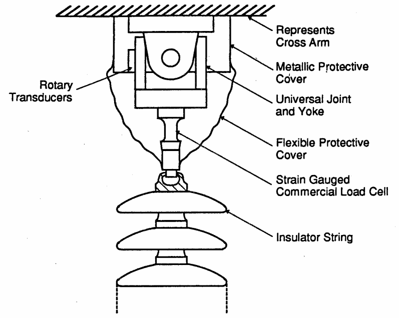

Fig. 2. Ontario Hydro "Transload" [13]

2) Newfoundland and Labrador

Reference [14] describes the use of four test spans with load cells to measure span tension operated in the winter of 1974-75 during studies of ice loading in Labrador. Although the conductor spans were removed after one winter, the towers were left standing and site visits to observe icing were made for some time afterwards.

Newfoundland & Labrador Hydro operated a number of ice monitoring test spans along the route of a proposed DC transmission line from 1979 to 1987. In the early 1990s, a test site was installed at Hawk Hill [15, 16]. The installation consists of two spans of wire between guyed single pole dead-ends with a guyed V tower between. Conductor tension is measured with a load cell at each dead-end. Load cells are included in one guy at each dead-end, the guys for the guyed V tower, and the conductor suspension point of the center tower. Tilt sensors are also included on the conductor attachment. One leg of the center tower has strain gauges to measure the forces in the leg. A heated Hydrotech anemometer and an unheated RM Young anemometer are mounted on the center tower. Other weather instruments include a Rosemount ice detector, a rain gauge and temperature and humidity sensors. Data is stored on site as well as transmitted to a computer at the utility offices in St. John's.

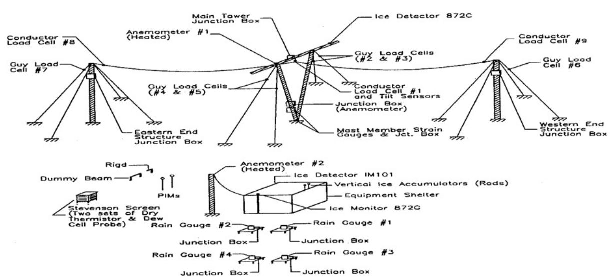

Fig. 3. Hawk Hill Test Site [15]

3) Quebec

Mount Valin: Reference [17] describes a test line installed on Mount Valin near Chicoutimi, Quebec in Canada in 1985. Fig. 4 shows the test span. Load cells were used to measure the cable tensions. The temperature was measured with a thermistor (temperature sensitive resistor). Wind speed and direction were measured with a "de-iced" anemometer. An ice detector was also installed. Signal conditioning and data acquisition was done on site with the results transmitted by telephone to a laboratory at the University of Quebec at Chicoutimi.

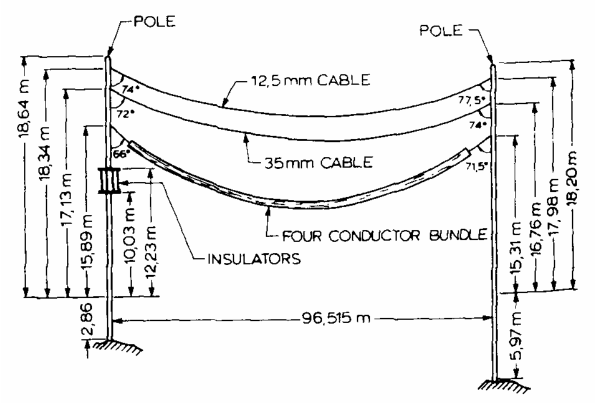

Fig. 4. Mt. Valin Test Span [17]

By 1995 the test site had two nearly perpendicular test lines. They were instrumented with load cells, a temperature gauge, an anemometer, an ice detector, a precipitation gauge, data loggers and a video-camera [18]. Reference [19] reports that a video camera monitors the main test line 24 hours per day taking one picture each 6 s. Other data is collected at 30 minute intervals and transmitted once per day by cellular telephone to a data base at the University of Chicoutimi.

Mount Belair: In 1994 Hydro-Quebec installed load cells in the I string suspension insulator of a 315 kV line and the V-string of 735 kV line [20, 21] at Mt. Belair. In addition five passive ice meters and two types of icing rate meters were installed. Air temperature, humidity, wind speed and direction and precipitation are also measured. Two video cameras were also installed with one that could be monitored remotely in Montreal. Data was transmitted by telephone land line, cellular telephone and satellite. In the first two years of operation approximately 15 icing events were recorded. See also [22]

In 1999 a new a new test line was added: three spans parallel to the transmission lines and one in the perpendicular direction [23]. It was equipped with three different conductors which are characteristic of those used on Hydro Quebec's distribution grid in rural areas. Sensors include 15 load cells with inclinometers, an ultrasonic wind monitor and thermometer. Two rain gauges are also included on the site. Readings are recorded every 15 minutes. By 2002 fourteen instances of ice storms had been recorded.

Lake Lavoie: Reference [24] reports *"The Lake Lavoie icing site at Lake Lavoie, on a similar 735-kV line, a four conductor bundle and a ground wire were also instrumented and measurements recorded during the 1996-2000 period. The Lake Lavoie icing site is also located in the Laurentian Mountain Range along the St. Lawrence River, approximately 60 km downstream of Quebec City. The conductors at the clamps are at an elevation of 799 m. The weight span of the instrumented tower is 212.5 m and a 11-mm steel ground wire with a 5.7 N/m weight is instrumented. Conductors are 31.6 mm in diameter weighing 19.4 N/m. Load cell measurements at Lake Lavoie make possible a comparison of icing loads collected on ground wires and bundle conductors."*

DGI: Reference [25] describes ice shedding events at the DGI test site in Quebec, which includes four lines with two spans, with each span 200 meters long. At this site the wire tensions and temperature are measured in real time with load cells and thermocouples respectively.

References [26, 27] report that Hydro-Quebec is installing equipment to de-ice transmission lines in Quebec using the joule effect. Load cells are being installed on suspension towers in operating lines to measure the weight of ice to determine when de-icing should begin.

The sites at Hawk Hill, Mt. Belair and Ottawa provided data for a Canadian Electric Association (now CEATI) study of ice accretion models [28, 29].

C. Czech Republic

Reference [30] compares calculated weights of ice deposits with those measured at the test stand at Studnice, Czech Republic. The test stand is described in detail by [31]. The following measurements are performed: ice measurements on conductors and measuring rods; measurements on samples of conductors; measurement of icing at different elevations; and tests of new sensors and equipment. This site has been operated continuously since 1940 with measurements of icing on short lengths of conductors of various diameters. This is arguably the best data set about icing in existence today. The current test site has been in operation since 1980 with two 250 m spans of conductor and also many short samples of different conductors.

D. France

Electricite de France's Luchon Experimental Station which was used for galloping studies is briefly described in [32]. The site has four 160 m spans with the capability of measuring overloads on the conductors, air temperature, and precipitation intensity. There is also a camera for filming conductor rotation.

E. Great Britain

EA Technologies and its predecessor The Electricity Council Research Centre began building an extensive network of test sites in the United Kingdom in 1988. It began with racks of conductor samples free to rotate about their own axes mounted on structures that acted as wind vanes, so the conductors were always perpendicular to the wind [33]. Test spans were added beginning in about 1991 at Green Lowther Hill in Scotland followed by test spans at Deadwater Fell (still operating) in 1992 and several other sites [34]. Tensions in the lines were monitored with load cells. CCD cameras with sensitivity at both visual and infrared wavelengths were used for time lapse photography. Illumination was provided at night. Weather conditions were also monitored. Information was transferred by telephone land line to EA Technologies' offices.

In 1996, both the samples in frames and the test spans were being monitored by time lapse video cameras 24 hours per day

[35]. The test spans had five frames recorded every three minutes from each of three different cameras. Pointers were installed on the spans to track rotation of the conductor. Data was recorded and stored on site as well as being telemetered in real time to EA Technologies where the data could also be viewed in real time.

EA Technology added a new test site in the Shetland Isles [36]. This site is reported to have "the most severe combination of wind and ice loads in the UK." The site was commissioned in 1995 and includes five lines with 3 spans and one with 2 spans. The monitoring equipment included video cameras with good low light sensitivity and infrared illumination at night. Load cells monitored the conductors along with wind speed, wind direction, temperature and humidity. This site also included accelerometers mounted on the poles and crossarms which were sampled at 150 Hz. This allowed the movement to be calculated and compared between poles and crossarms made of different materials. Data was sent by telemetry to Capenhurst. The data was displayed in user friendly format (see screen shots in [36]).

Reference [37] describes tests performed at Greenlowther, the Shetland Isles and Deadwater Fell on covered conductors.

Details of the Deadwater Fell site are updated in a paper on validating ice loads predicted from meteorological models [38]. In addition to conductor tensions, wind speed, wind direction relative to the structure, air temperature, liquid water content, and visibility (as seen by the video recording system) could be measured.

F. Iceland

Erection of test spans to determine ice loads in Iceland began in 1972 [39]. These typically were guyed poles with a span of wire and dynamometer as shown in Fig. 5. A method of determining the effects of the guys stretching was also described. The dynamometers were later changed to integrated load cell/data loggers that could record and store a full winter's data.

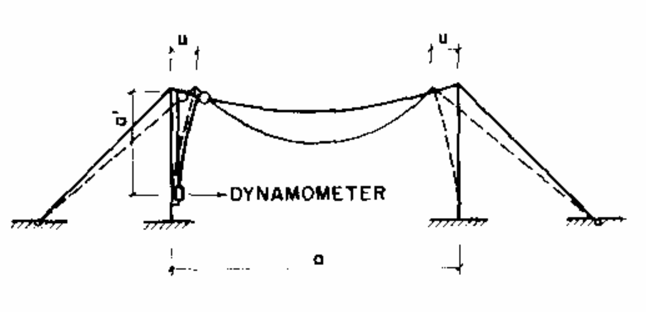

Fig. 5. Test Spans in Iceland [39]

Reference [40] describes a test span in an operating 66 kV line at Bolafjall near Hestakleif, Iceland. The test span began operation in 1991. The line has a load cell and inclinometer in a suspension insulator string. Two Rosemount ice detectors and heated wind speed and direction sensors are also included.

Reference [41] reports on the further development of tension monitoring equipment in Iceland. At that time, 35 tension recorders at 25 sites were in operation. Hugrún Ltd developed the recorders. The tension range is typically 0 to 100 kN. These are self contained units with load cell and data logger intended to be left unattended for long periods of time. They sample at 0.5 to 1 Hz and record the maximum, minimum and average values every 10 minutes. Temperature is recorded separately. A site at Hallormsstadarhals is described in this paper.

A test line near Fljótin in northern Iceland is described in [42]. The test line has two spans with the center structure used for measurements. Each of three phases is suspended from a tension load cell with integrated data logger which can operate automatically for one year. The conductor attachment points are all at the same elevation. As at Hallormsstadarhals, the data is measured at 0.5 to 1 Hz with the maximum, minimum and average loads recorded each ten minutes.

Reference [43] describes the ice load measurements that have been made in Iceland on test spans for the last 30 years. The sites are described as follows:

> *"Each test-measuring site has one, two or three spans lying in a straight line, at right angles or in a triangle. The spans are standardized, being 80m long. The conductors are strung on poles 10m above ground. Two types of conductors are used, 28 mm (AAAC) is most common, but 18 mm (AAAC) is used at few locations.*
>
> *During the first years, only mechanical maximum recording dynamometers were used and manual readings were taken three times a year. In 1988, electronic force recorders were first installed and since then, a few have been installed every year. Since 2005, all the operating test spans have been equipped with electronic force recorders. Precision and reliability of the recorders have improved greatly. The recorders measure tension at 0.5-1 Hz and store maximum, minimum and mean values within each 10 minutes. For a more detailed description of the set-up of the test spans and the force recorders, see references [4]. The original maximum recording dynamometers are still operated in all the test spans to ensure calibrations between old and new measuring methods. Since 2005, ambient temperature measurements are also made every 10 minutes at all the sites. In some locations, additional weather parameters are continuously measured as well.*
>
> *Measurements of the conductor's end tension are taken. They are then converted into external load per unit length, using the geometry of the test span and mechanical properties of the cable and guys."*

Fig. 6 shows a typical load cell and data logger detail [43].

Fig. 6. Test Span Load Cell and Data Logger Detail [43].

G. Japan

Reference [44] describes a test line that was operated for three years beginning in 1991 in anticipation of the construction of a new 500 kV line. Three towers and two spans were constructed. One span had a 4-conductor bundle and the other a six conductor bundle of TACSR/AS 410 mm^2. Load cells were installed in the subconductors on the conductor side of the insulators. Potentiometers were used to measure the catenary angle at the supports. Accelerometers to measure galloping were installed at the quarter span and midpoint of the span. Ice samplers were also installed on one of the towers.

A test line was built at the top of Mt. Takaishi in 1978 [45]. Tests there were still under way in 1998. Two separate single test spans were constructed using 4 towers. Solar panels and batteries are used for power. Wind speed and direction, temperature and span tension are recorded using analog recorders. Icing samplers are also installed at various elevations on the towers. Galloping observations at Mt. Takaishi are described in [46].

Reference [47] mentions the Mogami Test Line in Tachikawa, Yamagata Prefecture Japan which was used for galloping experiments.

H. Korea

A two span double circuit test line equipped with sensors to measure conductor ice loads in Korea is reported in [48].

A two span test line in the mountains of Japan is briefly described by [49].

I. Norway

Reference [50] provides a brief description of test spans in Norway. These are further described in [51].

Reference [52] describes using a video detection and image processing system that used five video cameras viewing different sections of the span. An image processing systems allows the two dimensional movement of the conductor during galloping to be determined.

J. Romania

Reference [53] describes a test site at Semenic, Romania that was put in service for the winter of 1984. It had three towers and two spans. At one end the conductor was attached to the ground with insulators. At the other end, they are attached to electric winches on the ground that allow the tension to be varied. At the middle of the first span, a meterological station to measure wind speed and direction. Short lengths of conductor were also mounted perpendicular to each other for measuring rime ice. Some damage occurred in the first winter that was repaired in the summer of 1985. The site is further described in [54]

K. United States

Reference [55] describes the use of a three axis load cell to measure ice and wind loads on a test span on Mount Washington in New Hampshire in the U.S. Note that the highest wind speed measured in the world to that time, 103 m/s (231 mph) was on Mount Washington. [56].

In October of 1993, the Alaska Energy Authority installed instruments on a 138 kV tower on Mitkof Island near Petersburg, Alaska [57]. The line is currently operating at 69 kV. The site includes a load cell and longitudinal inclinometer in the suspension insulators of all three phases. A transverse inclinometer is included in the center phase. In addition there is a weather station with a thermistor temperature sensor, a heated tipping bucket rain gauge and an unheated propeller anemometer and wind direction sensor. Data was collected by downloading the data at the site from two electronic data loggers onto a laptop PC. Data was collected from this site until the spring of 1998. Power is supplied from a transformer installed on a parallel distribution line.

The Anchorage-Fairbanks Intertie is 345-kV line currently energized at 138 kV. Since beginning operation in 1984 the line has had several outages caused by unbalanced snow loads. There have also been reports from people living and working in the area of low wires. An instrument system was installed in the fall of 1996 to detect unbalanced snow loads and to post alerts to the dispatch center that operates the line [58, 59]. The system includes 24 instrumented towers and two weather stations. Each tower has a load cell installed in the I-string insulator of the east phase with inclinometers installed on all three phases. Air temperature, battery temperature and power supply voltage are also monitored. The weather stations include Rosemount heated wind speed and wind direction sensors, a heated tipping bucket rain gauge with Alter shield, barometric pressure, relative humidity and air temperature. The rain gauges are on platforms to elevate them above the deep snow experienced in the area. Analog cellular telephones communicating with a modem equipped PC at the control center provided communications. Two of the towers were equipped with three 40 watt solar cells to recharge the batteries. The rest of the towers had only batteries which were replaced every one to two years. Since the original installation, solar panels have been installed at all of the towers. About 2 years ago the data loggers and cellular telephones had to be replaced because analog cellular service ended. The current system uses a mod bus system on digital cellular service. The original custom software was replaced with commercial data acquisition and display software. This system has been operating for 13 years.

IV. Commercial Systems

In the early 1980's utilities became very interested in determining the temperature and sag of the transmission conductors as the systems became more interconnected and the electrical loading of existing lines increased. This section describes commercially available systems and systems being developed for commercial application (in Beta testing).

A. CAT-1 Systems

The CAT-1, patented in 1993, measures the support tension at the un-energized end of a dead-end insulator assembly. The unit consists of two load cells to measure the force in two insulator strings. These are typically installed to measure the tension in line sections on both sides of the tower (Fig. 7). The package includes signal conditioning, analog to digital conversion, and communication of the tension in engineering units. An air temperature sensor and a "net radiation sensor" can also be included in the system. This "net radiation" sensor consists of a replica of a section of conductor that has similar thermal characteristics to a conductor. The temperature of this replica is measured to give a temperature corresponding to that of the conductor without any Joule heating. The primary measurements made are: conductor support tension, temperature of an un-energized conductor (net radiation sensor) and ambient air temperature. Several applications are described in [60-69] In 1996, it was reported [70] that 70 Cat-1 systems had been installed at 30 utilities with 45 of the systems in areas subject to icing.

Fig. 7. Cat -1 System (from www.cat-1.com)

B. Power Donut and Power Donut 2

The Power Donut was developed by Niagara Mohawk Power Corp. beginning in the early 1980s. Development was continued by their subsidiary NITECH in a joint venture with Product Development Services until 1991 when USI licensed the technology. USI purchased the rights in 2001. The original Power Donut is no longer available. A new model, the Power Donut 2 is currently in the "pre-commercial" phase with units installed in the U.S. Midwest for testing. Figure 8 shows the original Power Donut. Both models are powered by the line current through an inductive power supply. The original Power Donut measured the voltage, current, conductor surface temperature and air temperature. The data was transmitted to a nearby ground station by radio for transmittal to the utility. The Power Donut 2 measures line current, phase to ground potential, conductor surface temperature, angle at which the conductor is inclined at the Power Donut 2, internal unit temperature, battery voltage and power supply voltage. Communications options include a GSM Cellular telephone or spread spectrum radio.

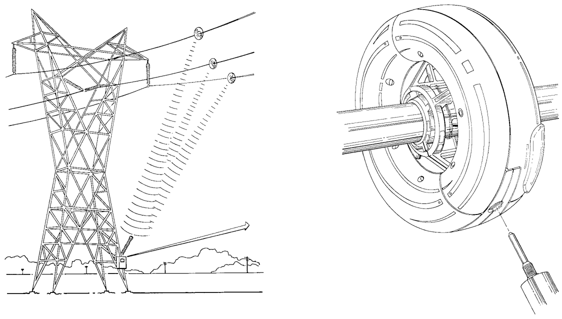

Fig. 8. Concept of Original Power Donut [71]

C. Sagometer

The development of the Sagometer was sponsored by EPRI and the California Energy Commission. It is marketed by EDM International, Inc. It has a target fastened to the conductor, typically at a distance of about 50 m (150 ft) from the structure. The target is illuminated at night. A video camera is aimed along the line and image processing software is used to locate the target within the fixed image field of the camera, see Fig. 9. The unit includes an inclinometer to measure the tilt of the camera and an ambient temperature sensor. The primary measurements made are the vertical and horizontal location of the target (and thus a point on the wire), the inclination of the camera and the ambient temperature. The manufacturer says transmitting the pictures is technically feasible, but this has not yet been attempted.

Camera and Control Box | Target

Fig. 9. Camera and Control Box Target [72]

D. EPRI

EPRI is currently testing is a "Backscatter Conductor Temperature Sensor" that measures conductor spot temperatures. The sensor communicates with a nearby base station using the same technology as the radio frequency identification (RFID) tags that are being used on retail merchandise.

E. Ampacimon

The Ampacimon was developed at the University of Liege in Belgium. One of its developers is Dr. Jean-Louis Lilien, who has participated in previous IWAIS conferences. The Ampacimon has accelerometers to measure two sets of three-axis accelerations. From this data, the natural frequencies of the span can be determined, which in turn allows the sag to be calculated directly, without needing the span length and elevation difference. From the sag, the ampacity can be determined. This device also measures the frequency, magnitude, and fatigue cycles due to Aeolian vibration. It also can provide information about the magnitude and duration of galloping. This sensor is mounted on the conductor and harvests power from the transmission line. Communications are by low power radio or GSM cellular telephone.

Fig. 10. Ampacimon (photo from Destiné & Lilien, University of Liege)

F. Lindsey/INL

This line monitoring device was developed at the U.S. Idaho National Laboratory. The impetus for its development was the wide-spread sabotage of high voltage transmission towers in Iraq. This device is intended to alert the operator to threats in the immediate vicinity of the tower. It is mounted on, and harvests power from, the conductor. Sensors include a two-axis accelerometer, an infrared detector, and an ambient temperature sensor. Detection of people on or near the tower is determined by analyzing the signals from these sensors. This device is currently being developed for commercial applications by Lindsay Manufacturing Company. With suitable signal processing, this device could also provide information about the sag, Aeolian vibration, and galloping.

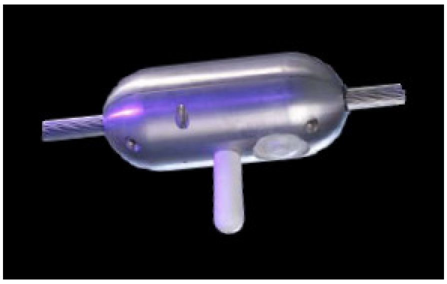

Fig. 11. INL/Lindsey Transmission Line Security Monitor (photo by Idaho National Laboratory)

G. Promethian Devices

The Promethian Device HVTL-STAC measures the electric and magnetic fields of a three phase transmission line. From these measurements, the sag, phase current, conductor temperature and ampacity can be calculated. Three sets of sensors, one for each phase, are installed at ground level or buried slightly below the ground surface. No monitoring equipment is installed on the transmission line itself. The system is powered by solar panels and batteries, and communications are by GSM cellular telephone.

H. Protura Line Sensor

The Protura Line Sensor measures the spot temperature of the air, a spot temperature on the conductor, and the distance of the instrument from the ground, or an object or snow on the ground, using a laser distance measuring device. It has a digital camera which can transmit pictures. It also includes a galloping alarm, and measures rotation about the conductor axis.

I. RIBE and Arteche

Systems for spot temperature measurements are marketed by RIBE and Arteche Group. RIBE's RITHERM uses a surface acoustic wave sensor [73] that is powered and read remotely. Arteche's SMT is powered by the line current and uses a cellular telephone for communications.

J. Other Systems

In addition to the commercial systems, there are some interesting systems that have either been tried but not commercialized or are in development. They include:

- Laser Distance Measurements [74, 75]
- GPS Location [76, 77]
- Fiber Optics [78]
- Induced Currents [79, 80]

V. Structural Health Monitoring

Real time monitoring of transmission lines shares many characteristics with the larger discipline of structural health monitoring. Reference [81] defines health monitoring as follows:

> *"Health monitoring is the scientific process of nondestructively identifying four characteristics related to the fitness of an engineered component (or system) as it operates:*
> - *The operational and environmental loads that act on the component (or system),*
> - *The mechanical damage that is caused by that loading,*
> - *The growth of damage as the component (or system) operates, and*
> - *The future performance of the component (or system) as damage accumulates."*

One of the most ubiquitous examples of structural health monitoring (SHM) is the use of tire pressure sensors in most new automobiles; these alert the driver to possible tire problems.

Structural health monitoring of bridges is a particularly active area of both research and application. In August 2007, the bridge carrying U.S. Interstate Highway 35 over the Mississippi River in Minneapolis, Minnesota collapsed, killing 13 people (see Wikipedia for more information). The replacement bridge, designed by Figg Engineering Group, incorporates 323 sensors [82]. These sensors monitor the health of the bridge and provide real world measurements to researchers interested in bridge design. Sensors include vibrating wire strain sensors in the concrete; temperature sensors on the top of the bridge deck and on the underside of the bridge; accelerometers near the center of each span; long-gauge strain gauges in the main span; linear potentiometers that monitor movement of the expansion joints and bearings; and corrosion sensors to monitor corrosion in the reinforcing steel. The sensor outputs can be read in real-time over the internet. Alan Phipps of Figg Engineering Group is quoted as saying: "this is just a way of starting off on the right foot with this new bridge. It provides information on how to maintain the bridge, starting with day one. We think this kind of structural health monitoring is going to become more and more common in the future."

Structures constantly have low level vibrations that can be detected by sensitive accelerometers. These vibrations are induced by ground shaking due to earthquakes, including very distant ones. Nearby traffic and wind also induce vibrations. All structures have natural frequencies at which the structure resonates. The amplitude is limited by inherent damping in the structure. These natural frequencies can be determined by analyzing the signals from accelerometers. This analysis provides a "signature" for the vibration characteristics of the structure. A study of the Long Beach, California Public Safety Building is described in [83]. This building was instrumented with 14 state-of-the-art strong motion accelerometers. They were placed at different locations and orientations throughout the building. A structural seismic upgrade of the building was then carried out and the changes in the characteristic vibration signatures of the building were recorded and studied. These types of studies are used to verify that the finite element models used in design provide realistic predictions of the structures' response to earthquakes.

We can speculate that the vibration signature of a transmission structure would change significantly if the structure were covered in ice.

SHM of aircraft was recently highlighted in the crash of Air France flight 447 over the Atlantic Ocean. The aircraft's ACARS (automated communications and reporting system) sent several messages in the minutes before the aircraft disappeared indicating an electrical fault and pressurization problem [84]. These systems also provide information to maintenance personnel to be prepared to repair an aircraft when it arrives at its destination.

Climbing inspections of lattice transmission towers look for, among other things, loose bolts and damaged or fractured members. Reference[85] reports research on using sensors to detect loose bolts. In this research, a piezoceramic patch is used to excite the structure with a small impulse load and then to sense the resulting vibrations. They have had some success analyzing changes in the characteristic vibration signature of the structure to determine whether bolts have loosened, and where the loose bolts are.

An example of the progress made in the miniaturization of sensors and communications capabilities is Apple's iPhone. The iPhone has an accelerometer. Its primary use is to orient the display; however, applications also have access to the accelerometer. For example, one application is a bubble level. The iPhone also has GPS location capability as well as the ability to locate itself in relationship to Wi-Fi hot spots and cellular towers. It also includes a digital compass, camera, and connection to the worldwide web. This technology demonstrates the types of capabilities that can be included at low expense in a mass-produced product.

VI. Components of a Monitoring System

Monitoring systems have four main components: sensors; data acquisition and communications; and power supply.

A. Power Supplies for Load Cells, Inclinometers and Weather Stations

Traditionally, systems that include load cells, inclinometers and unheated weather instruments have been powered with solar power supplies. The U.S. Snow Load Monitoring System, which used cellular telephones for communication, has two sites that have been successfully operating at 61° N latitude for 9 years on solar power supplies [58, 59]. This system minimizes power usage by turning the cellular telephones on for 5 minutes every 2 hours. The batteries are starved electrolyte lead acid batteries which are freeze tolerant. The six batteries used for each system can supply power for a complete winter without requiring any contribution from the solar panels. The solar panels are sized to completely recharge the batteries in the summer months.

Instruments mounted on conductors with sufficient current are able to harvest power from the magnetic fields. The Ampacimon, Protura Line Sensor, and the Lindsey INL device all use this type of power supply. One disadvantage compared to other power sources is the difficulty of storing power for use during outages. Some of the most interesting icing data may be lost if there is an extended outage.

Research in batteries for all applications from power grid scale to individual sensors is advancing rapidly [86]. Advanced lead acid batteries are being developed which have activated carbon added to the negative electrode, which results in a three to four times improvement in cycling life. Lithium ion batteries are also undergoing rapid development and are widely used in portable power tools and consumer electronics. At the same time, solar panel prices are decreasing as mass production increases to meet the demand for grid-connected solar power supplies.

The high power requirements of heated anemometers and rain gauges generally preclude the use of solar power supplies. If distribution service is not available, thermoelectric generators are available with capacities of up to 5,000 watts. "A thermoelectric generator converts heat directly into electricity with no moving parts. As heat moves from a gas burner through the thermoelectric module, it causes an electrical current to flow. The heart of a Global thermoelectric generator is a hermetically sealed thermoelectric module (thermopile), which contains an array of lead-tin-telluride semiconductor elements" [87].

If the instruments are located near a transmission line, station service voltage transformers with adequate capacity are available for nominal line voltages up to 230 kV [88].

There is tremendous research and development going on today for fuel cells to power cars, which would also have the capacity to operate heated anemometers and rain gauges. We can expect rapid improvement in the next few years in remote site instrument power supplies.

B. Sensors

Sensors are available to measure a wide variety of structural parameters, in addition to those discussed above which concentrate on conductor sag and tension measurements. The I-35 bridge discussed above has examples of many of the sensors available for civil infrastructure.

Individual sensors that have built-in conversion to engineering units and also direct Ethernet connectivity are beginning to come on the market (www.microstrain.com). Some of the newer sensors are based on fiber optics, which include displacement, strain, vibration, temperature, chemical sensing, and acceleration.

The technology for radio frequency identification (RFID) is now being used for passive sensors which are remotely powered by the reader. These surface acoustic wave devices are already being used to measure torque in rotating equipment, pressure transducers, temperature sensors, and scales. The RIBE RITHERM uses this technology to measure transmission conductor temperatures; in this case, the passive sensor must be within about 15 meters. Low power readers have the capability of reading a sensor up to two meters away.

Self-powered wireless sensors are under development [89]. The power would be generated from the ambient vibrations of the structure.

C. Data Acquisition and Communications

Traditional sensor systems have data loggers which convert the sensor signals to engineering units; they have many communications options (www.campbellsci.com). These include telephone land lines, cellular telephones, satellite telephones, Wi-Fi networks, Ethernet, and spread spectrum radios. Many radio systems today can increase their range by hopping from one data logger to another until they reach the base station.

Sensor nets specifically for structural health monitoring are in development. References [90, 91] describe the specific application of sensor networks to electric power systems. A sensor net would provide "wide area surveillance with the collaboration of cheap, smart, and unattended sensors networked through communication links and deployed in large numbers."

VII. Future Benefits

The recent advances in sensors, power supplies, and data acquisition/communications are making it simpler and more cost effective to monitor structures in real time. In the past, the primary emphasis of real time monitoring of operating lines, as opposed to test spans, has been to determine conductor sag to allow power transfer to be maximized. It is now feasible to not only monitor sag, but also to monitor environmental loads and the condition of structures and foundations. Monitoring can provide warning of damage to transmission lines before failure occurs; this will improve reliability. Data from real time monitoring will allow routine maintenance to be scheduled more intelligently, which will also reduce costs and improve reliability.

Sensors will also provide information to improve the quality of design loads and methods of analysis by allowing comparison between theory and real world data.

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