Application of Sensor Network for Secure Electric Energy Infrastructure

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***Abstract*—Wireless sensor networks are becoming the technology of choice for sensing applications mostly due to their ease of installation and associated lower costs. This paper proposes a novel conceptual design for an application of wireless sensor technology for assessing the structural health of transmission lines and their implementation to improve the observability and reliability of power systems. A two-layer sensor network model is presented for overcoming the communication range limitations of smart sensors, and two operational modes for enhanced energy efficiency are introduced. Simulations integrating the output of the sensor network with an energy-management system were conducted, obtaining improvement in the security of the power system.**

***Index Terms*—Energy-management system (EMS), network sensitivity factors, power system security, power transmission lines, wireless sensor networks.**

I. Introduction

With the increasing threat of terrorism around the world, more attention is being paid to the security of the electric transmission infrastructure. Experiences in countries like Colombia, which has faced as much as 200 terrorist attacks on its transmission infrastructure per year [1], demonstrate the vulnerability of the power system to these kinds of events. Although it is very difficult to avoid or predict when and where these terrorist acts can occur, quick assessment of the situation can help operators to take optimal actions to avoid cascading events and the consequent partial or total blackouts.

The mechanical failures resulting from malicious attacks on a transmission line are basically the same as those that would result when extreme natural events affect a portion of the transmission line. Thus, any analysis conducted in this regard can also help in taking preventive and corrective action when acts of sabotage are directed on the transmission infrastructure.

The current method to assess the damage caused by any unexpected physical event on the transmission grid is the visual inspection of the transmission infrastructure [2]. With problems that occur in concentrated environments, like substations or generating plants, it is not difficult to find and assess the damage with a fairly small crew or with adequately localized video surveillance. But in transmission lines which are geographically dispersed over hundreds of miles, this task is more difficult. Nevertheless, once an event occurs, the operator in the control center only receives indication that an electrical fault occurred, but not if it is temporary or permanent. Therefore, the operating standards state that he/she has to try to reinsert the faulted line in order to check the temporary/permanent condition of the event. Once all of the attempts fail, then the line is marked as permanently out of service. The recent blackout events in the U.S. [3] and Italy [4] have shown that failure to assess and understand the condition of the power system and delay in taking appropriate corrective actions after just a single outage can lead to widespread blackouts of large areas of the power system.

We propose the utilization of wireless sensor network technology for detection of mechanical failures in transmission lines such as: conductor failure, tower collapses, hot spots, extreme mechanical conditions, etc. The proposed application involves the installation of sensors for mechanical monitoring in predetermined towers of a transmission line and communicating via a wireless network. The main goal is to obtain a complete physical and electrical picture of the power system in real time, diagnose imminent as well as permanent faults, and determine appropriate control measures that could be automatically taken and/or suggested to the system operators once an extreme mechanical condition appears in a transmission line.

For evaluating the feasibility of the concept, a dispatcher training simulator (DTS) based on the energy-management system (EMS) platform from AREVA T&D was used for simulating the operation of the electric power system in real time as it is monitored at an actual energy control center.

II. Mechanical Characteristics of Overhead Transmission Lines

A. Transmission Lines Components

The design of overhead power lines conceptually considers them as composed of four individual components: foundations, supports, interfaces and conductors, all of which have limited mechanical strength [5]. The design process takes into account the coordination of the mechanical strengths since the failure of one of the four components may lead to the collapse of the entire transmission facility.

When the different components of a transmission line are subjected to their limits of strength, their failure could be sudden, occurring in fraction of seconds and can result in instability, rupture or complete separation; or it could be progressive, resulting in loss of strength that eventually leads to damage after long periods of time.

There are two main types of support structures, strain and suspension supports.

Strain and angle-strain supports carry the conductor tensile forces in the direction of the conductor and serve as rigid points in the line. They are designed for conductor tensile forces differing in both line directions and to provide protection against

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cascading structural failures. For long, straight line sections, strain supports are placed every 3 to 6 miles [5].

At suspension supports, conductors are fixed to suspension insulator sets, carrying the conductors in a straight vertical position, swinging in the prevalent direction of the conductors. They are not designed to transfer conductor tensile forces to the supports other than for abnormal conditions, given that the design provides for the longitudinal forces to cancel in both directions. Any medium to large imbalance can potentially produce the collapse of the entire structure.

Given its relatively lower cost, large sections of a transmission line are compounded by suspension supports. Thus, because of its construction characteristics, when a failure occurs on any of the suspension members of a determined section, there is a very high probability of collapse of the remaining suspension supports in the affected section, producing a *structural cascading failure*.

B. Mechanical Loads on Structures

Overhead transmission lines, by the nature of their exposed constructional characteristics are subjected to loads imposed by the environment such as wind, ice, snow, earthquakes and flooding; and also to human related hazards such as accidents and terrorism. The effects of these loads produce detectable forces in the components of the line that can affect their ability to withstand the operating conditions.

Three different categories of wind induced conductor motion are recognized, being differentiated by their frequency, amplitudes and effects on conductors, interfaces and supports [6]. Aeolian vibrations are the most common. Their main characteristics are small amplitude and relatively high frequency. They increase the tension stress on lines, produce conductor "turn" and create vibration on the structures [5]. Conductor gallop is another form of wind effect characterized by vertical low frequency and high amplitude conductor motion. It is usually caused by relatively strong and steady winds on asymmetrically iced conductors [6]. Galloping magnifies loads in a conductor and especially the vertical end forces on the supports [7]. The third form of effect is the wake induced oscillation. It is peculiar to bundled conductors, and occurs when relatively moderate or strong winds act upon the line. Experience has shown that damage is largely localized in a few places on the line.

Accumulation of snow and ice on conductors affect them in a two fold way. It increases the tensile forces on the wires due to the added weight, and additionally changes their aerodynamic characteristics by changing the shape of the surface exposed to the wind, with the effects related to those described previously.

The effects of human related events over transmission lines can be detected by the same set of sensors intended to monitor the effects of winds and ice because any accidental or malicious event involves some kind of disturbance over the normal mechanical operating characteristics of the line. The extent of the damage caused by any accidental or malicious event cannot be predicted since it depends on many variables.

In October of 2003, in Oregon and California, there were some reported cases of bolt removal from the legs of 500 kV transmission lines [8]. The act was apparently aimed at weakening the mechanical strength of the structures; however, no mechanical collapses occurred. There have been reports in the U.S. of cutting guy wires of strain/dead-end structures [9], also, reports from U.S. and Colombia show that cutting the legs of lattice towers is a method used by saboteurs [1].

Bombing produces a more direct impact over transmission structures and is widely used as the main form of attack over the electric infrastructure [1]. The impact of bombing a transmission line support goes from collapse of the entire structure to limited damage at the point of placement.

The explosive blast produced by a bomb placed at the foot of a transmission structure produces vibration by means of the direct impact of the expansive wave and indirectly due to ground induced vibration [10]. The duration of the vibration phenomenon depends on a series of factors, from the size of the explosion to the constructive characteristics of the support. If the blast is not powerful enough to produce a complete collapse of the support, it would probably produce a tilt of the tower. In this case, differential longitudinal stresses can appear in suspension supports and increased tension can be detected in strain/dead-end supports.

C. Temperature Concerns

The effect of the current flow on the rise of temperature on the conductors is well known. The loading calculations presented in [11] establish thermal limits for determined weather conditions and conductor characteristics.

Hot Spots present another concern of temperature rise in transmission lines, appearing in the coupling between energized conductors and the interfaces. The appearance of hot spots may degrade the mechanical reliability of conductors and connectors producing a thermal runaway situation that could lead to catastrophic failure of the point of attachment. Once a hot spot appears, a reduction of the current flowing through the line is in order until it can be repaired.

III. Proposed Wireless Mechanical Sensor Network

A. Proposed Sensor Selection and Placement

There are a number of sensors capable of monitoring mechanical variables on the line that could be used to detect abnormal conditions when extreme environmental events or human related accidents or sabotages appear. Since transmission line support structures have constructive characteristics closely related to building structures, it is proposed to use a set of sensors based in that application, where researchers have found that the utilization of acceleration, strain and displacement sensors can provide an appropriate level of observability for earthquakes and wind [13], [14].

Given that temperature is also a concern in electric energy transmission; the application can take advantage of the sensing infrastructure to place temperature sensors at the attachment point of conductors to detect possible hot spots and overheating problems related to overloads.

Table I presents an application matrix for selected sensors and their response to any mechanical event appearing on the line. This is based on observed characteristics following the event.

It is proposed that tension or strain sensors will be mounted at the interfaces of the strain supports. It is recommended to install them at all the conductor attachments of all strain structures because of their important role in maintaining the physical integrity of the transmission line. This results in a high level of observability on any transmission line for mechanical events that involve change over normal tensile conditions, such as high winds, ice accretion or compromise of the structural integrity of surrounding structures.

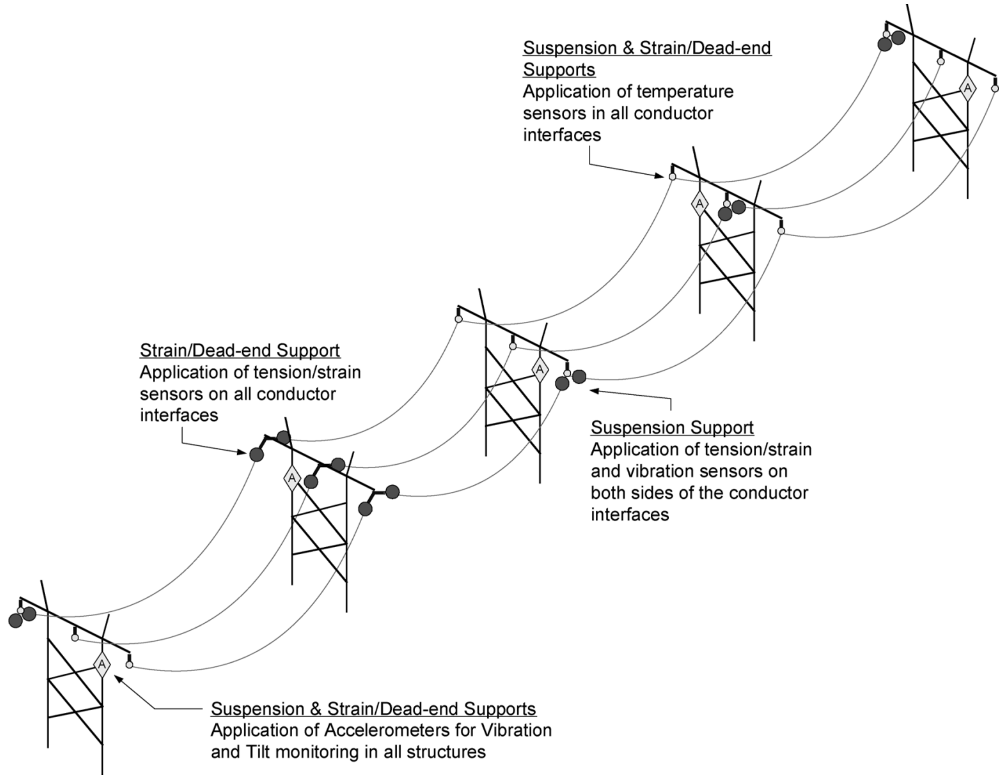


Fig. 1. Overview of the proposed sensor placement.

TABLE I
SENSOR APPLICATION MATRIX

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

For a more complete assessment of the mechanical conditions of the line, as in detecting the unlikely event of an isolated failure, it is recommended to measure tensile forces on conductors attached to a number of suspension supports, placing them on both sides of the point of attachment of the conductors at every third tower. In this manner, each support monitors only one phase conductor, but the system does not loose observability because each attachment point not being monitored directly is monitored by an adjacent support. The overview of the recommendation is shown in Fig. 1.

We propose the installation of accelerometers in the support body for vibration and tilt monitoring, and in the conductor attachment points for detecting wind induced vibration. Installation in conductors is recommended for maintenance optimization, but if cost is a constraint, their application can be omitted.

Installation of temperature sensors for the detection of overheating can be optimized given that heating conditions due to overloads are uniform in relative long portions of the line. However, since hot spots are highly localized phenomena, they can only be detected by placing temperature transducers close to all the points of attachment of conductors. Again, cost is the determining factor for selecting the complete application for hot spots.

It should be noted that all the measurements from the proposed sensors are related in various ways. The relationship can be between different sensors applied to the same structure, as in the case of tension and strain, or between vibration and tilt, or it can be between the same kinds of sensors at different locations, as in the case of strain sensors applied to the conductors at both ends of a suspension interface.

Additional event classification can be obtained by taking into account the difference on the dynamics of the failures. Wind and ice accretion do not appear suddenly; in the case of winds, they increase in time with deteriorating climatic conditions. Ice buildup is a progressive phenomenon that gradually adds weight to the conductors, consequently, increasing tension and strain in them. Accidents and sabotage are sudden; their effects may appear as a sharp increase of the sensed variables. An act of sabotage involving weakening of the structure can be distinguished if there is a collapsed structure in which no anomaly in the variables was previously detected.

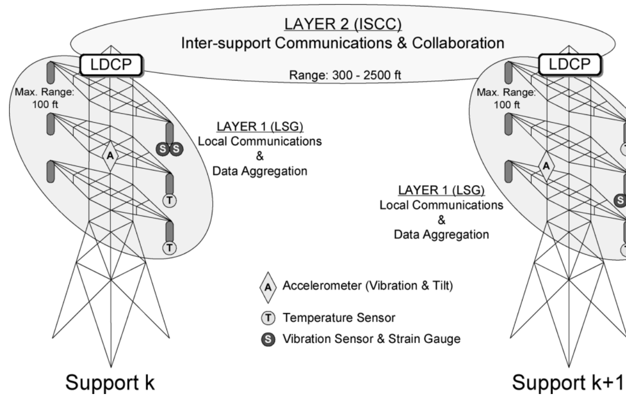


Fig. 2. Two layers model.

B. Proposed Architecture of a Wireless Sensor Network for Transmission Lines

For the recommended implementation of a *wireless mechanical sensor network* (WMSN) for transmission lines, the localization of each node is determined in the pre-deployment phase, with sensors of particular characteristics placed in predefined locations along the support structures and conductors. The total cost of deploying the WSMN would depend on the cost of the sensor package, installation cost, and maintenance cost. The cost of a typical sensor package depends on the various physical quantities that it measures (variable cost) and the cost of wireless transceiver (fixed cost), and it is typically in the range of few hundreds to one thousand US dollars. The installation and maintenance costs depend on the geographical spread of the transmission line (flat surface, terrain, forest, etc.) and other factors which is beyond the scope of this paper. The sensors can be programmed to implement one or more communication protocols, which can be activated on need basis.

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 linear 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 comes with an increased communication 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 come 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 full mode*) are proposed for the WMSN.

In the proposed operating principle, a *local substation processor* (LSP) at one end of the transmission line commands the start of a data collection sweep, interrogating the first LDCP. The message control header will contain the parameters indicating if the sweep corresponds to partial or full operation mode, thus, instructing the LDCP what kind of processing to apply to its contents and its own data from the LSG. Directionality is achieved by including the sender and receiver address in the message header. In this manner, when a substation initiates a sweep, it places a zero value on the sending node address and 1 as the receiving node. This will instruct LDCP_1 to process the message and broadcast it to the next LDCP. This process will continue until the sweep reaches the substation's LSP at the other end of the line. Then, that LSP will trigger a data collection sweep in the opposite direction by placing its address $(n+1)$ as the sending node and n as the receiving node.

The message body contains a vector of data values and the associated addresses of the sensor nodes from which those values come. The size of the vector depends on the operating mode, being larger for full mode and reduced for partial mode.

In the partial mode, messages exchanged by the LDCPs contain only a reduced set of the total data present on every LSG. It contains the maximum value of each variable group (vibration, strain and temperature) and its associated sensor localization. As a consequence, the size of the message is small enough to provide high communication speeds. However, the time response characteristics that can be obtained from the WMSN do not make it viable for fast acting applications like primary or backup protection. On the other hand, it is suitable for integration with the data acquisition functionality provided by the SCADA system. In the partial mode, various complete line sweeps could be executed within one SCADA cycle.

The full mode collects the status information from all the sensors in the transmission line, enabling the LSP to obtain a complete picture of the mechanical status of the line. With the information obtained, the LSP can execute verification algorithms oriented to detect any inconsistencies within the collected data. Since the message size in this mode is larger than in the partial mode, bandwidth utilization is also larger. For that reason, it should be expected that end to end transmission would be significantly higher than that of the partial mode.

Failure detection of any LDCP is provided by means of implementing a timeout function in the preceding (sender) LDCP. Thus, when there is no receiving confirmation from the next LDCP, it is marked as a broken link and the sweep reverses direction, relaying the failure information to the initiating LSP. This could lead to further analyses for establishing if there was in fact a mechanical event (from measurements around the broken link) or just a LDCP failure.

1) Time Response Characteristics: Failures in the transmission system that involve grounding of phase conductors, or contact between them, induce short circuits that require to be cleared in the shortest possible time. Electrical protection equipment has been used since the inception of the electric grid for taking the appropriate corrective actions in a fast, selective and reliable manner. Common response times for clearing faults are in the order of 50 to 100 ms. Therefore, for the WMSN to be a plausible tool to carry out protective functions and provide fault signaling with adequate timing, messages from the faulted element should reach the substation in about 50 to 100 ms through the WMSN. This is an almost impossible requirement for today's technology, because of limitations on bandwidth and processing speed at LDCPs. Hence, it is concluded that the WMSN cannot be used to provide principal or backup protective functionality. On the other hand, the WSMN technology can be used to satisfy a slightly coarser timing requirements, such as the SCADA system. The SCADA collects information from the substations typically every 4 s. Therefore, it would be desirable that the LSP at the substation achieve at most one overall diagnostic of its supervised lines for every SCADA cycle. Given the latter requirement, it is expected that the transmission for delivering a complete information package from one end of the line to the other, plus the processing time at the substation, should not exceed the SCADA cycle time. For small size messages, this communication requirement can be satisfied with current technology.

IV. Proposed Tool for WMSN/EMS Integration

A. Mechanical/Electrical System Failure Modes

As discussed in Section II, the mechanical health status of a transmission line can be influenced by the environmental conditions and by human actions. The severity of the mechanical status can be established by comparing the values of the variables against the different limits defined by the design of the transmission line. A classification for the mechanical status is introduced here as follows:

- *Normal (N)*: There are no indications of variables being outside the normal operating limits. Tensions are within design parameters and balanced at suspension supports. Vibrations are minimal, and structures are in the vertical position.
- *Suspicious (S)*: Some of the variables are outside the normal range. Ice accretion, strong winds or maximum thermal loading can be events associated with this status. There could be measurable vibration and the inclinometers detect small tilt angles.
- *Imminent (I)*: Several variables are outside the thresholds for detecting mechanical problems, but there is no clear indication of a mechanical failure. High vibration levels are detected and structure's tilt angles are measurably different from the vertical. Although an indication of failure is not present, this condition deserves attention from the power system operator since it could be an indication that there can be an electrical failure and/or a network topology change some time soon.
- *Fault (F)*: Mechanical failures can be detected by the WMSN in different ways, by the excursion off limits of some variables, by values near to zero in others, or by the complete lack of signal from the sensors. Tension sensors indicate a broken conductor by detecting abnormally high or low values. Collapsed structures would be detected by tilt angles close to the horizontal.

The transitions between the proposed 4 states establish the permanent or temporary nature of a failure and their dynamics can establish the natural or human nature of a mechanical event.

In normal operation and even under high wind/ice conditions in which there is no compromise of the mechanical integrity of the line, it is unlikely that electrical faults will occur unless vegetation plays a role. Therefore, a direct relation between the WMSN and the electrical protective elements of the line is not expected. When events develop leading to a compromised or a completely failed structure, it is expected that the conductors will have a contact or grounding, resulting in phase to phase, phase to ground or even three phase short circuits. In this case, high correlation can be obtained between the output of the electrical protective equipment and the output of the WMSN.

B. IPSS Software

For each of the different failure modes, different actions need to be taken in the power system in order to avoid cascading events that could lead to a collapse of the interconnected power system. For testing the feasibility of using the WMSN, we focused on transmission overload management driven by the fault classification. That is, if a line trips and that produces an overload in another transmission line, the fault classification provides two ways to handle the event. For a temporary fault, the recommended actions are to wait and try to reclose the faulted line in a few minutes due to the purely electrical nature of the fault, but for a permanent fault, the recommendation begins with blocking any further reclosure and immediate initiation of the recovery process that can include generation rescheduling and/or load shedding.

By using the network sensitivity factors proposed by Wood and Wollenberg in [19], the power injections that contribute most to a line flow can be identified by examining the resultant *generation shift distribution factor* (GSDF) vector for a particular line, taking into account that any change in the power injection is compensated by a change in the opposite direction by the slack bus. It is to be noted that the GSDF factors depend on the network configuration and also generation and load pattern. Under different contingencies these factors change. In this paper, without loss of generality, the GSDF factors have been applied to illustrate the potential benefit of using mechanical sensors data in operations setting to aid operator decision making.

For determining the combination of injection increase and decrease that contribute most to line flow changes, it is necessary to first identify the node with the maximum value of GSDF in the original GSDF vector as

$$a_{l,pivot} = \max\left(|a_{li}|\right).$$

Then, the GSDF of each node referenced to the pivot is obtained by

$$a_{li}^{pivot} = a_{li} - a_{l,pivot}.$$

Once this is established, the combination of injections that contribute the most to line flows can be selected by taking the previously obtained *pivot node* and the maximum value of the new GSDF^{pivot} vector (*opposite node 1*). In the same manner, the second most contributing combination is identified by selecting the second largest (*opposite 2*) and the second smallest (*pivot 2*) values of the GSDF^{pivot} vector. We use the previously identified set of four nodes for determining the appropriate changes in their injections for managing the overload in a particular line. If the generation at the nodes obtained is involved in the AGC function, the next largest or smallest node will be selected.

The direction of generation change for each node depends on the signs of both the line power flow and the GSDF vector. When the *opposite 1* and *opposite 2* nodes have the same sign as the line flow, they have to decrease generation in order to alleviate the overload. When they have different signs, they have to increase generation. The *pivot* and *pivot 2* nodes change generation in the opposite direction of the *opposite nodes*.

Once the nodes to reschedule generation are identified, the generation allocation for each direction of change (up or down) that would provide the fastest overload relief in the line can be established by

$$\Delta P_i^{up/down} = \frac{Ramp_i^{up/down}}{\sum_j a_{lj} \cdot Ramp_j^{up/down}} \Delta f_l$$

where

$\Delta P_i^{up/down}$	change of generation required in unit i;
$Ramp_i^{up/down}$	unit i generation rate of change;
a_{lj}	GSDF value for the unit j referenced to line l;
Δf_l	overload in the line l .

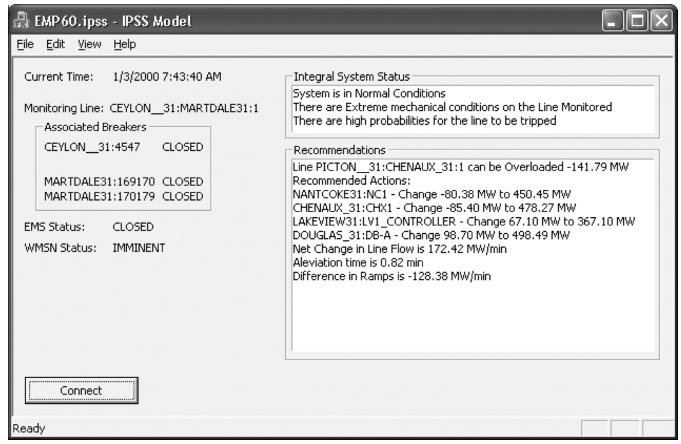


Fig. 3. IPSS output.

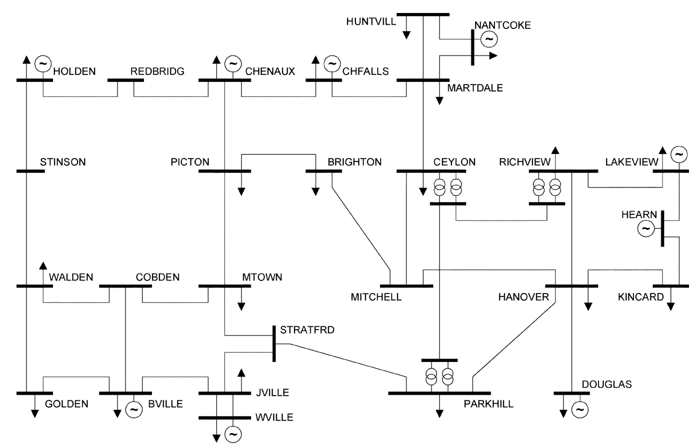


Fig. 4. EMP60 test system.

A Visual C++ program was developed for implementing the generation shift strategy previously described. The *integrated power system security* (IPSS) program performs the real-time assessment of the mechanical/electrical situation collecting the power system's electrical status data from the EMS/DTS and the mechanical status information from the WMSN every 8 s. An xml data file produced by the central processor supplies the mechanical status information to the IPSS, while the interface with the AREVA e-terra platform is built on the DDE service provided by Microsoft Windows, using AREVA's HABDDE server.

The mechanical/electrical status processing flowchart is presented in the Appendix wherein option exists to classify faults into imminent, suspicious, or permanent using sensor data.

The IPSS user interface is shown in Fig. 3.

V. Simulation Results

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.

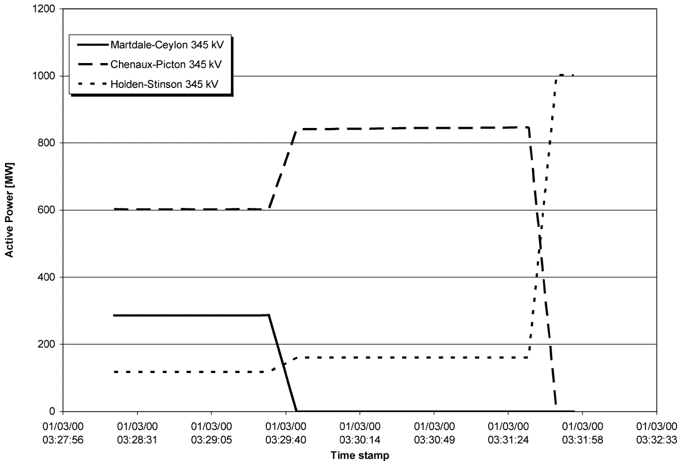


Fig. 5. Line flows–collapse case.

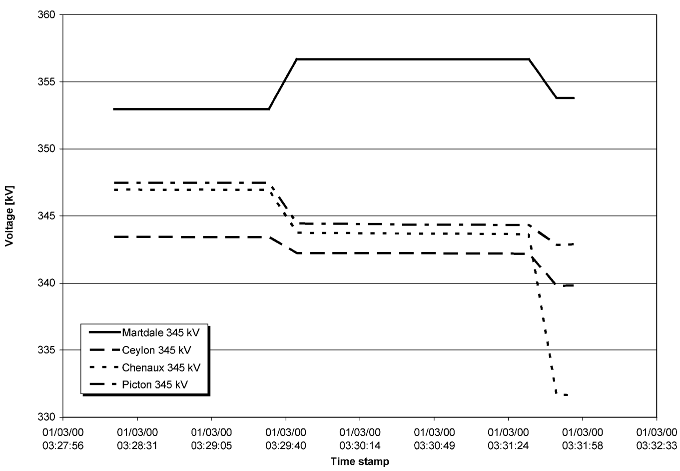


Fig. 6. Voltages–collapse case.

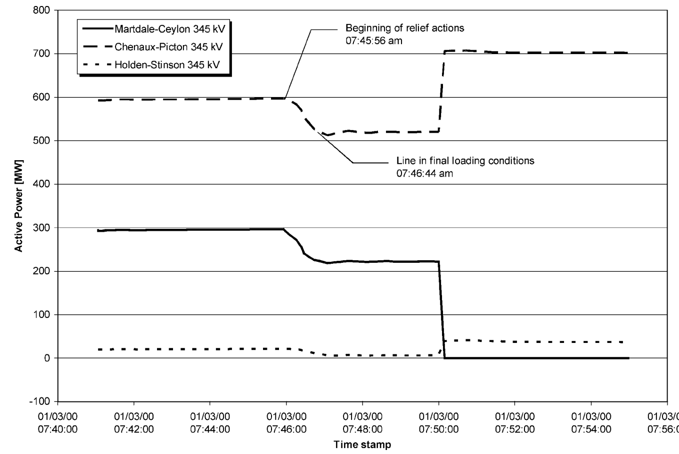


Fig. 7. Line flows showing relief actions–imminent fault case.

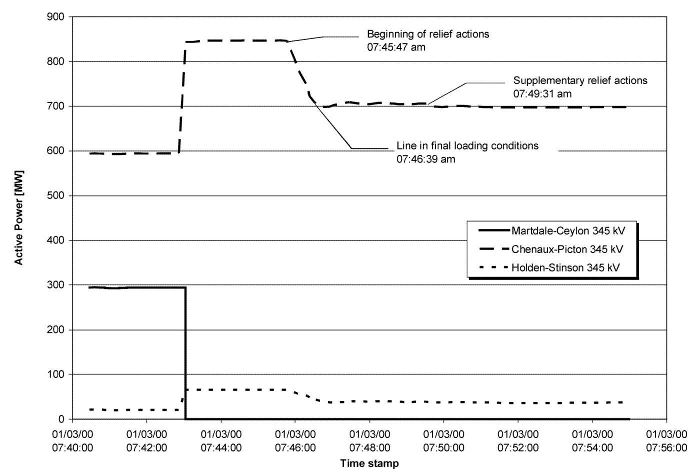


Fig. 8. Line flows showing relief actions–sudden fault case.

TABLE II
GENERATION SHIFT RECOMMENDATIONS

Plant	Generation Change
Nanticoke	- 80 MW
Chenaux	- 85 MW
Lakeview	+ 67 MW
Douglas	+ 98 MW

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.

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.

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).

If the outage of Martdale–Ceylon is sudden (i.e., without a progressively deteriorating mechanical condition), the combination of WMSN and IPSS can help the operator to take fast and appropriate actions to reduce the time interval during which the line Chenaux–Picton is overloaded as shown in Fig. 8.

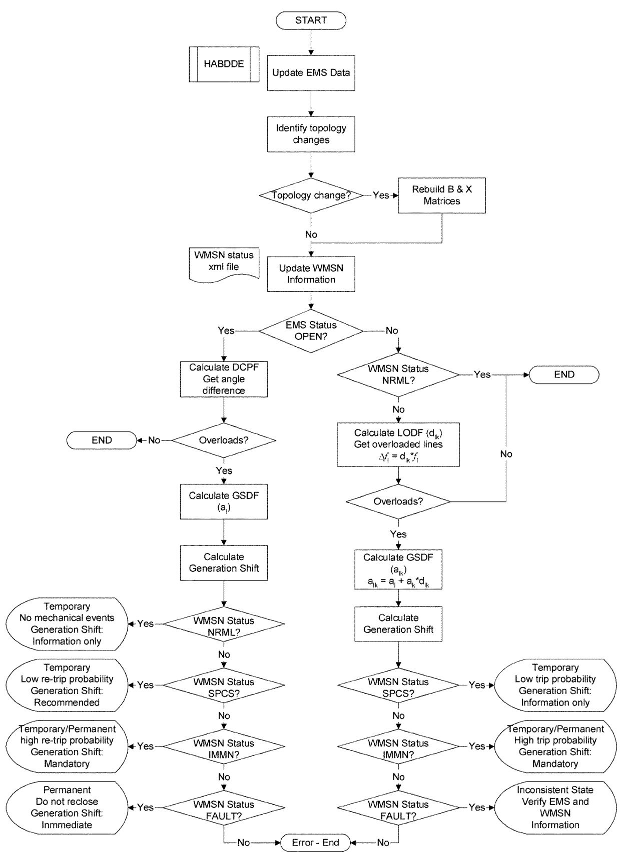
VI. CONCLUSION

This paper proposed a novel approach for using wireless sensor technology to assess the mechanical health of transmission lines. The proposed two layers architecture provides an approach to overcome the range limitation of the smart sensors installed in the supports, while offering a complete monitoring environment for a transmission line.

The simulation studies show that the WMSN can help operators take fast and appropriate decisions based on the mechanical failure modes detected by the WMSN.

Optimized maintenance practices can also be achieved by the analysis of the measurements provided by the proposed sensor system. Collected statistical information about stress and vibration in conductors can help maintenance engineers to optimally schedule preventive maintenance in lines with excess mechanical stress. The ability to detect hot-spots can provide surveyors with select locations to perform more thorough infrared analysis in structures. Our current work focuses on developing models that establish the relationship between various physical quantities and the eventual fault scenarios, and integrating the model into state estimation and other applications.

Appendix
Status Processing Flowchart



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