Sensor network design for a secure electric energy infrastructure

by

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Signatures have been redacted for privacy

To Claudia and Maria Teresa,

the source of my inspiration.

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CHAPTER 1. INTRODUCTION

With the increasing threat of terrorism around the world, more attention has been paid to the security of the electric transmission infrastructure. Events in countries like Colombia, which has experienced as much as 200 terrorist attacks on its transmission infrastructure per year [1], show 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 the optimal actions in order 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 done in this direction 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 occurring 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. Distance protection in transmission lines can provide an approximated localization based on the impedance calculation of a fault [3]. However, this result can be affected by a variety of conditions present in the fault that can change the actual impedance measured. Nevertheless, once one of these events occurs, the operator in the control center only receives indication that an electrical fault has occurred, but not if it is temporary or permanent. Therefore, the operating standards state that he/she has to try to reinsert the faulted network element in order to check the temporary/permanent condition of the event. Once all the attempts fail, then the element is marked as permanently out of service. The recent blackout events in the United States [4] and Italy [5] 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.

This thesis is the first work of an interdisciplinary group at Iowa State University working on innovative technologies for defense against catastrophic failures in power systems. It is intended to provide a novel approach to the technologies involved in the implementation of a sensor network design for a national electric energy infrastructure, and to establish the feasibility and the impact of using mechanical sensors to improve the robustness of power systems against catastrophic failures.

The task of monitoring the structural integrity of transmission lines helps in assessing the effects of mechanical events and designing strategies to deal with them in a controlled manner. The purpose of using wireless sensors for collecting structural information from the transmission system is to provide a complete seamless sensing environment thanks to their main characteristics: ease of installation and replacement, low cost, networking and small size.

This thesis proposes 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 new design involves the installation of mechanical sensors in predetermined towers of a transmission line, communicating via a wireless network. Some examples of the sensors involved are accelerometers, tension/ strain gauges, and tilt and temperature sensors. The main goal is to obtain a complete physical and electrical picture of the power system in real time, and determine appropriate control measures that could be automatically taken and/or suggested to the system operators.

Secondary goals of this thesis work include:

- Examine the practicality of the application of wireless sensor technologies to improve power system security.
- Propose a set of sensors suitable for the identification of physical problems in the transmission lines.
- Propose a basic architecture for the wireless system.
- Identify possible applications for increasing power system reliability and survivability based on the information collected in the field.

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.

CHAPTER 2. MECHANICAL CHARACTERISTICS OF OVERHEAD TRANSMISSION LINES

Overhead transmission lines, by the nature of their exposed constructional characteristics are subjected to forces imposed by the environment such as wind, ice, snow, earthquakes and flooding; and also to human related hazards such as accidents and terrorism. They are geographically dispersed over hundreds of miles between interconnecting substations and their conductors are maintained at secure heights above ground by support structures (usually poles or lattice towers). These supports are hundreds of feet apart from each other resulting in the conductor forming catenary curves.

Table 1. Common values for the spans of transmission lines

Voltage Level	***Minimum Span [ft]***	***Average Span [ft]***	***Maximum Span [ft]***
115 – 138 kV	600	700	800
345 kV	500	900	1500
500 kV	950	1200	1500

A literature review [6] gave approximate normal values for spans of transmission lines of various voltage levels as shown in Table 1. It is to be noted that due to the different methods and technologies for constructing transmission lines, the results presented in Table 1 represent just a small population of the transmission lines in existence. They help to establish a reference frame for later discussion of the required range for wireless communications. In practice, spans can be as short as tens of feet and as long as 3000 feet for special crossings.

Components of a transmission line

The designing process for overhead power lines conceptually considers them as composed of four individual components as shown in Figure 1: foundations, supports, interfaces and conductors, all of them having limited mechanical strength [7]. The design takes into account the coordination of the mechanical strengths required due to the fact that the failure of one of them may lead to the collapse of the entire transmission line.

When the different components of a transmission line are subjected to their limits of strength, their failure behavior will also differ. For some components, the failures could be sudden, happening in a matter of fraction of seconds and can result in instability, rupture or complete separation. For some others, the failures are progressive, resulting in loss of strength that eventually leads to damage after long periods of time.

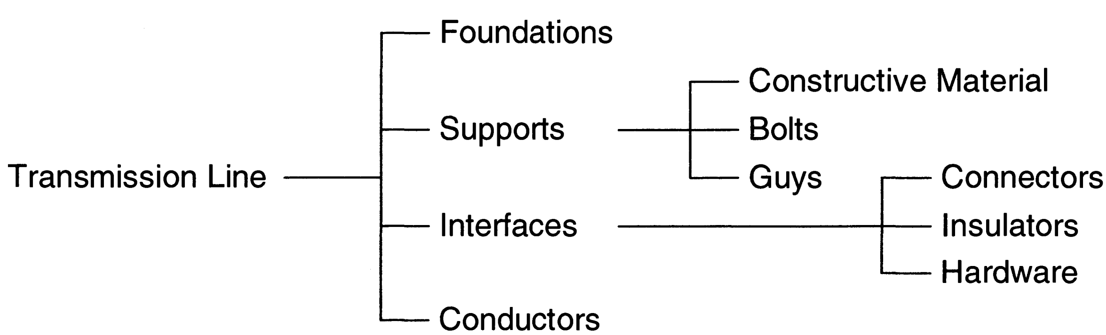


Figure 1. Transmission line components

Foundations are the components designed to transfer the loads resulting from maintaining the conductors above ground into the subsoil with enough reliability. Foundations generally contain a combination of concrete and steel, and their construction depends on the terrain characteristics. Failures involving this component are almost always terrain related or ground level occurrences such as flooding, terrain sliding, earthquakes or bombing attacks.

Supports, the most visible components of a transmission line, can be constructed with a variety of materials and designs. They are the link between the power line conductor's assemblies and the ground, and their most important components are the towers or poles. The supports are composed by the pole body, cross arms and earth wire peaks and their constructing material can be wood, reinforced concrete and/or steel. Their main function is to withstand reliably the conductor forces and external loads [7]. Failures involving these components can be due to a direct effect of the environment or due to induced efforts by the foundations on the ground side, or the conductors on the overhead side. The design of transmission line supports calls for sustaining a range of credible mechanical stresses in an economically optimal way. Additionally, support design also takes into account the proper required clearances to ground and between conductors. See Figure 2.

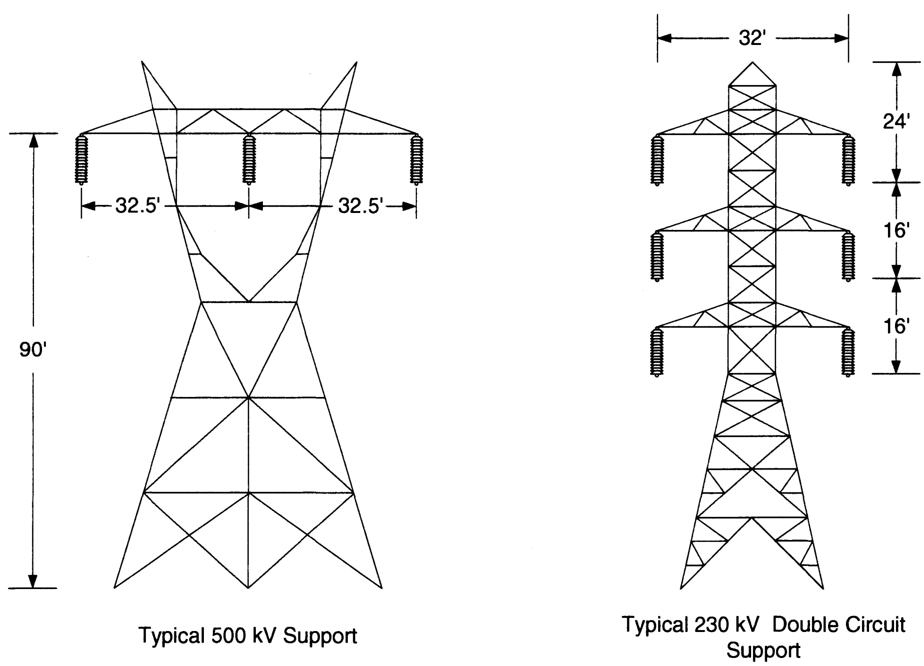


Figure 2. Typical dimensions for 230 and 500 kV supports

The *interfaces* are the components that join the conductors and the supports. Their application defines the kind of mechanical loads that will be transmitted from the conductors to the towers or poles. The most visible component of the interface is the *insulator*, which enables the proper electrical insulation, while providing mechanical attachment between the live conductors and the earthed parts of the supports. The actual elements connecting the conductors to the insulators and those to the supports are the *fittings*. They provide the appropriate degrees of freedom for the interface assemblies to follow the movement of the conductors without transmitting it to the supports [7]. Failure of these components is mainly a product of transmitted stresses from the conductors, rather than from the direct impact of the environmental conditions.

Conductors are the means for the electric energy to flow from one transmission line end to the other. A continuous path of conductive material between both ends is required. This requirement means that the conductors also provide mechanical connection between the different structures that support them above ground. Conductor construction is comprised of copper or aluminum and for high voltage transmission also includes a steel core for mechanical strength. Motion induced by the environmental conditions (wind, ice, etc.) produces progressive weakening of the mechanical strength of the conductors at their point of coupling with the structures and also vibration in the different components of a support site. Sudden conductor breaking can also be a product of excessive tensional forces or direct impact of an external agent as in the case of accidents or terrorist attacks.

The particular arrangement of the four main components in each structure determine the kind of forces it can withstand, and therefore, determines the role each support plays in maintaining the structural integrity of the entire transmission line.

Support types and applications

An extended definition of support will be used in this thesis for discussion simplicity. In this case, a support will be defined as the complete set containing the foundations, support structure (tower or pole) and the interfaces between the conductors and the tower arms.

Ideally, supports should be constructed robustly enough to sustain a broad range of mechanical events, and that on failure, the impact will not be propagated to the other components of the transmission line. On the other hand, if ideal conditions were always present on the line, the conductors could be laid on the supports carrying only their weight, without any worries about forces other than gravity affecting the supports. However, real conditions and economics play a role in the design of a transmission line, forcing the combination of both aspects.

In order to withstand the different forces applied to the structures due to conductor loads, different type of supports are used:

Suspension supports

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. Since this task does not require extremely strong mechanical characteristics, this kind of support is cheaper. Thus, long line sections are composed of this type of structure, in between strain or dead end supports.

Interfaces at suspension supports are lightweight and pivoted, providing freedom for conductors to swing. Mechanically, the design provides for the longitudinal forces resulting from the product of gravity and wind to cancel in both directions of a suspension interface, resulting in just the weight of the conductor plus ice accretion loads to be carried by the set of interfaces and supports. Only residual amounts of longitudinal stresses and vibrations are transferred to the supports. Therefore, the supports are not designed to withstand large amounts of longitudinal forces. Any medium to large imbalance can potentially produce the collapse of the entire structure.

Angle suspension supports are also part of this category for changes of line direction between 0° and 20°. In this case, the suspension insulator sets assume an inclined position, while maintaining residual force transference to the supports.

Conductors are subjected to higher stresses at the attachment point than in the longitude of the span. As noted before, the forces actuating the interfaces fittings can induce bending stresses in the conductors that can ultimately force them to fail. In the free span, static tensile stress and small static and dynamic bending stresses are present [7]. In the vicinity of the attachment point, higher tensile and bending stresses can appear depending on the environmental conditions and conductor motion.

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 *cascading failure*. Strain supports are placed regularly in transmission lines in order to avoid the extent of the damage.

Strain, Angle-strain and Dead-end 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 cascading structural failures. For long, straight line sections, strain supports are placed every 3 to 6 miles [7].

Dead-end supports carry the longitudinal tensile forces of the conductors in just one direction. These supports can be subjected to high torsional loads if only one circuit is installed on double circuit structures.

Interfaces in strain and dead-end supports must be able to carry the tensile forces exerted by the conductors. In this case, the complete longitudinal force is transferred from the conductor to the interfaces and to the support structures (poles or towers). The support structures are designed to carry any imbalance produced by different span lengths or difference in environmental conditions such as ice accretion or wind. Additionally, they are designed to prevent failure if all the conductors on one side break, limiting the amount of damage from cascading failures on the faulted side of the line. Regularly placed strain supports offer the required failure limiting characteristics in transmission lines.

From the description of both suspension and strain/dead-end supports, it can be inferred that ultimately, strain/dead-end supports experience any major longitudinal effort occurring in any section of the line between two of them as shown in Figure 3. This conclusion will be used in later sections to establish the minimal requirements for sensor placement in order to obtain proper observability of the mechanical health of a transmission line.

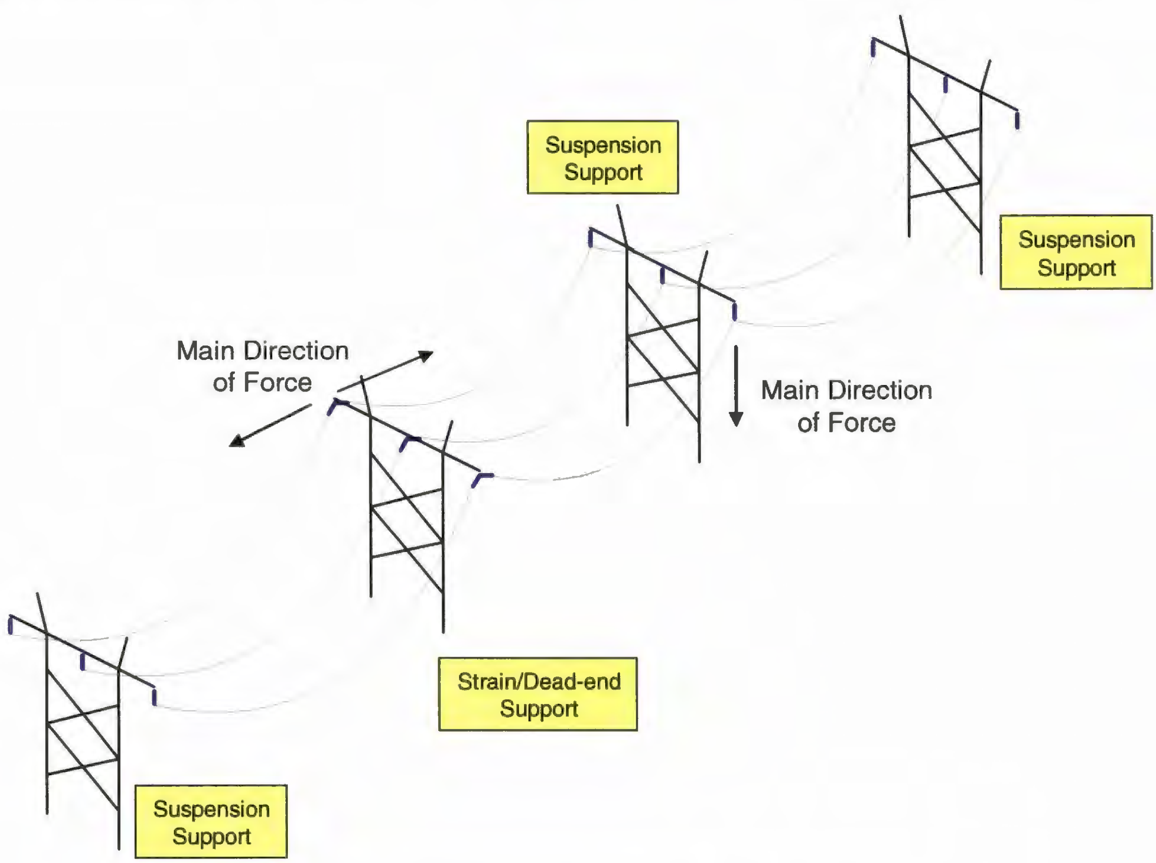


Figure 3. Types of support and main acting forces

Mechanical loads on structures

Given the constructive characteristics of overhead power lines, it is apparent that they are exposed to a variety of loads produced by weather conditions, accidents and intentional malicious acts. The effects of these loads produce detectable forces on the components of the line that can affect the ability to withstand the operating conditions. The different types of loads and their effect on the components of the transmission line are treated in the following sections.

Base loads

Gravitational (Vertical) and tensile (Horizontal) loads are present in the structures as a result of the force exerted by the conductor own weight.

The static loads on an undisturbed transmission line are not very large and do not influence the design calculations in more ways than setting a starting point [17].

Wind

Wind flowing around conductors produces alternate movements on them due to the creation of vortices at the top and bottom of the conductor [8]. These vortices produce alternate pressure unbalance, causing up-down movements on the conductors at right angles to the direction of the wind. Three different categories of cyclic conductor motion are recognized, being differentiated by their frequency, amplitudes and effects on conductors, interfaces and supports.

<u>Aeolian Vibrations</u>: Are the most common form of vibration appearing in transmission lines. This kind of vibration appears under relatively low wind speeds and certain relative directions. Its main characteristics are small amplitude and relatively high frequency. It increases the tension stress on lines, produces conductor “turn” and creates vibration on the structures [7]. Reference [15] presents a technique for predicting the permissible level and duration of vibration that a conductor can withstand before failing, when monitoring data is available.

The first failures attributable to aeolian vibrations were observed in USA around 1924 [13].

Conductor Gallop: This phenomenon is characterized by vertical low frequency and high amplitude conductor motion. It is usually caused by relatively strong and steady winds on asymmetrically iced conductors [8]. The extreme motion that characterizes this phenomenon makes it particularly dangerous for a transmission line, since it can damage conductors, interfaces, and even compromise the structural integrity of the supports.

Galloping magnifies loads in a conductor and especially the vertical end forces on the supports [9].

Wake Induced Oscillation: This type of oscillation is peculiar to bundled conductors, and occurs when relatively moderate or strong winds act upon the line. It is produced by the shielding effect of the conductors directly exposed to the wind. The kind of orbits drawn by the conductors ranges from up and down movements, to circular or elliptical oscillations. It can produce damage limited to suspension interfaces and spacers; experience has shown that damage is largely localized in a few places on the line.

Table 2, taken form [8] presents a summary of the characteristics and effects of the three types of cyclic conductor motion.

Table 2. Comparison of types of cyclic conductor motion [8]

	Aeolian Vibration	***Conductor Gallop***	***Wake-Induced Oscillation***
Types of Lines Affected	All	All	Lines with bundled conductors
Approx. Frequency Range (Hz)	3 - 150	0.08 - 3	0.15 - 10
Approx. Vibration Amplitude (In conductor diameters)	0.01 - 1	5 - 300	Rigid Body Mode: 0.5 - 80 Subspan Mode: 0.5 - 20
Weather Conditions Favoring Conductor Motion			
Wind Character	Steady	Steady	Steady
Wind Velocity	1 - 7 m/s (2 - 15 mph)	7 -18 m/s (15 - 40 mph)	4 - 18 m/s (10 - 40 mph)
Condutor Surface	Bare or uniformly iced	Assymetrical ice deposit on conductor	Bare, dry
Design Conditions Affecting Condutor Motion	Line Tension, conductor self-damping, use of dampers, armor rods	Ratio of vertical natural frequency to torsional natural frequency; sag ratio and support conditions	Subconductor separation, tilt of bundle, subconductor arrangement, subspan staggering
Damage			
Approx. time required for severe damage to develop	3 months to 20+ years	1 to 48 hours	1 month to 8+ years
Direct causes of damage	Metal Fatigue due to cyclic bending	High dynamic loads	Conductor clashing, accelerated wear in hardware
Line Components most affected by damage	Conductor and shield wire strands	Conductor, interfaces and structures	Suspension interfaces, spacers, dampers, conductor strands

Support members can also experience fatigue as a result of vibration induced from the conductor. Vibration controlling devices are used to diminish the effect on the support. However, direct excitation of support members appear to be less common than secondary excitation from conductor action.

Snow

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 in the previous section. Additionally, by conduction of forces, increased tension and stress occur at interfaces and supports. Therefore, its influence tends to worsen the mechanical conditions experienced by transmission lines members.

Vibration on supports

Being exposed to the elements, transmission line supports are subjected to dynamic forces not only caused by conductor motion, but by the effect of weather or nature on them. Wind, snow, earthquakes, and terrain instability, among others can cause a direct impact on structure integrity. However, industry experience has shown that vibration on supports and their members rarely occurs and has seldom caused destructive failures. Only isolated occurrences have been reported [17].

Accidents

There are a variety of accidental events that can affect the mechanical stress on transmission lines. Since they are distributed members of the power grid, they are exposed to all kind of animal and human activities.

A report from Magaña, Cathcart & McCarthy states that collision with transmission line wires are the first cause of helicopter accidents in the United States [18].

In the category of accidental occurrences, component failures can also appear due to defect, wear, fatigue or the complete failure of a transmission line support due to extreme environmental conditions such as earthquakes, tornadoes, hurricanes, landslides, etc.

The majority of the events falling into this category can seldom be described statistically due to their inherent random nature. In fact, the extent of the damage caused by any accidental event cannot be predicted since it depends on several variables. As an example, Figure 4 shows a general aviation airplane stranded on a high voltage transmission line after an accident, without resulting in the collapse of the line supports which could be expected from an accident of this magnitude.

Figure 4. Plane accident over transmission lines

However, the effects of accidents over transmission lines can be detected by the same set of sensors intended to monitor the effects of winds and ice. Any accident involves some kind of disturbance over the normal mechanical operating characteristics of the line. In the previous example it is obvious that the added weight over the conductors creates excess longitudinal stresses on suspension and strain/dead-end supports. The main difference between accidental and wind/ice effects relies on the characteristics of the failure, since it is very likely that an accident occurs suddenly, creating a sharp surge of stress over the conductors and supports, while failures related to wind and/or ice can build up stresses over time until a failed component appears on the line.

Malicious intentional events

One of the first events that come to mind when treating terrorist attacks and sabotage actions is the placement of explosive devices. Nevertheless, they are not the only modality of sabotage intended to disrupt the physical integrity of the transmission network.

In October of 2003, in Oregon and California, there were some reported cases of bolt removal from the legs of 500 kV transmission lines [19]. The act was apparently oriented to weaken the mechanical strength of the structures, however, no collapses occurred. This kind of act resulting in the weakening of the structural integrity of supports has been used widely for sabotaging transmission lines. There have been reports in the U.S. of cutting guy wires of strain/dead-end structures [20], also, reports from U.S. and Colombia show that cutting the legs of lattice towers is also a method used by saboteurs.

These kind of covert acts do not directly impact any of the mechanical variables of longitudinal stress or vibration but reduce the strength of the supports for withstanding any abnormal conditions. The consequence of this is that any environmental event that could be inside the design parameters of the line can now produce collapse of the weakened structure.

Bombing produces a more direct impact over transmission structures and is widely used as the main form of attack over the electric infrastructure. Its main purpose is to produce the immediate collapse of the affected structure, which does not always happen. It has been noted that lattice towers are less prone to be affected by explosions than rigid construction poles mainly due to their open construction characteristics in which most of the expansive wave is dispersed through the gaps between frames [1]. The impact of bombing a transmission line support goes from collapse of the entire structure, to limited damage at the point of placement. Figure 5 and Figure 6 show the result of bombing attacks on two structures in the Colombian power system, where there was complete collapse and limited structural damage respectively.

Figure 5. Collapsed structure due to bombing.

Figure 6. Tilted Structure due to foot damage

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],[11]. 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. However, it is not expected to remain for prolonged periods of time due to the natural damping provided by the structure. If the blast is not powerful enough to produce a complete collapse of the support, it would probably produce a tilt of the tower (as shown in Figure 6). In this case, differential longitudinal stresses can appear in suspension supports and increased tension can be detected in strain/dead-end supports. The treatment for collapsed structures is basically the same as for collapses induced by extreme environmental conditions.

In the case of explosion, the mechanical effects appear suddenly and are expected to fade in time, therefore, sensing for these conditions have to be made in short intervals or by means of continuous monitoring.

Similar to accidental events, it is not clear how to statistically model the probability of occurrence of a malicious event. They can only be dealt with after their occurrence.

Temperature concerns

The effect of the current flow on the rise of temperature on the conductors is well known. In fact, power transfer limits on transmission lines are imposed by determining the maximum temperature at which the conductors can be operated reliably. Normal transfer limits are associated with the ability of the conductor to sustain the normal operating temperature in a continuous manner. Emergency limits are established by relating the temperature rise with the time the conductor spends in this overloaded state without generating permanent damage. Based on this principle, a common practice for emergency limits is to use 130% overload during 30 minutes [12]. The loading calculations presented in *IEEE standard for calculating the* *current-temperature relationship of bare overhead conductors* [12] establish limits for determined weather conditions and conductor characteristics. However, since transmission lines extend over hundred of miles, weather conditions can be very dissimilar among different sections of the line. In addition, because of construction requirements, transmission lines may contain different conductor types in different sections. The common practice is to establish the section of the line with the most critical combination of average weather conditions and conductor types and from it, calculate the appropriate steady state and transient current ratings.

In addition to the usual temperature effect, there is another concern about temperature rise in transmission lines. *Hot Spots* appear in the coupling between energized conductors and the clamps belonging to interfaces fittings. The term *Hot Spot* stands for regions of high temperature difference between the conductors and interfaces at the conductor coupling. They are not directly caused by conductor loading, but often their temperature rise is influenced by it. Their origin is related to deficiencies in the attachment of the conductors to the insulators. They commonly appear because of a loose connection or by the use of narrow clamps applying pressure in a narrow portion on the conductor [2]. 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. Figure 7 shows a hot spot on a conductor coupling in a high voltage transmission structure [14].

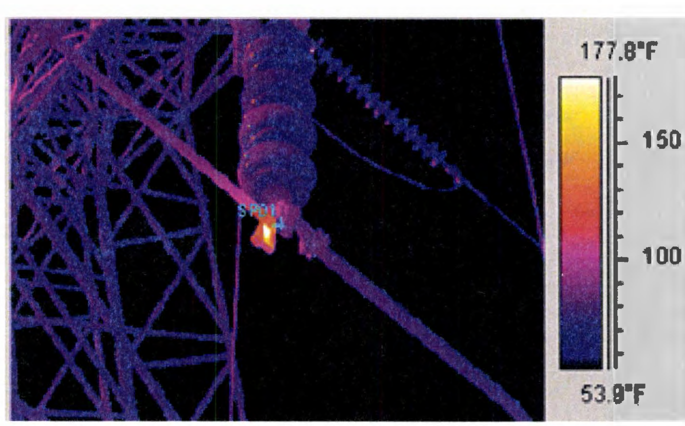


Figure 7. Hot Spot in a conductor coupling [14]

Once a hot spot appears, a reduction of the current flowing through the line is in order until it can be repaired. The industry practice is to limit the normal power transfer capability of the line, thus, reducing power flows on the transmission line. Failing to do so could lead to deterioration of mechanical strength in the hot spot location and the consequent damage and long term unavailability of the transmission line.

Allowable limits

The National Electric Safety Code (NESC) is a voluntary standard that provides the basic provisions for guaranteeing the safety of persons during the construction, operation and maintenance of electric supply and communication equipment. It is not intended to be a design manual; it provides minimum requirements for the design of electric power lines. In the case of overhead electric transmission, it establishes clearance, loading and strength requirements.

However, the limits established by the NESC are generally considered inadequate for standard ACSR and aluminum conductors [21]. Recommended practices for maximum allowable tension in percent of conductor strength are presented in Table 3, extracted from [21].

Table 3. Recommended Maximum Tension Limits in percent of conductor rated strength.

	ACSR Conductors	*All-Aluminum Conductors*
Initial Unloaded	33.3%	30.0%
Final Unloaded	25.0%	20.0%
NESC Loading District	50.0%	50.0%
NESC Extreme Wind	70.0%	60.0%
Extreme Ice	70.0%	60.0%

Reference [16] presents a comparison between the tension requirements of NESC and IEC, with similar values as the ones presented here. The recommended tension limits shown in Table 3 can provide a starting point for establishing the thresholds at which a sensor application can trigger warnings and alarms when confronted with abnormal mechanical conditions in a transmission line. This topic will be revisited in Chapter 6 to establish the mechanical failure modes present at any instant in a transmission line.

Mechanical failures on overhead power lines due to the environment and sabotages

A transmission line behaves mechanically like one continuous body, with the conductors as the main links between the support structures. In very rare circumstances, there is a truly isolated mechanical failure. In almost all cases the failure of one structure produces a chain reaction which generates a *cascading failure*.

When a failure occurs in a suspension support and produces the separation of the conductor from its attachment point, the tensile stresses on the adjacent supports increase to almost double [22]. This effect arises because now each one of the supports must carry the weight of the two adjacent spans. Even, if the spans are short enough and there are parts of the interfaces still attached to the conductors, the stresses can be greater than double. As a consequence, the adjacent supports tend to be tilted to the center of the "doubled" span. If the forces acting are sufficient enough, they will also collapse. This dynamic continues until a sufficiently strong dead-end support stops it or when enough slack is developed in the conductors of the failed section to equilibrate the resultant longitudinal tension. The latter is usually called the *Domino Effect*. Therefore, once a failure occurs, it is transmitted to a number of supports which will, in general, suffer similar mechanical failure characteristics.

Nebraska Public Power District experienced the failure of 266 consecutive supports in the line Grand Island – Moore 345 kV on July 8, 1993. An analysis of the event, which is believed to be caused by extreme wind conditions, is presented in [22]. According to the paper, winds approaching 100 – 125 mph affected the structures in an ample area through the line. In determined points, loads on supports were in the order of 4000 to 6400 pounds, producing their collapse. Subsequently conductors and structures failed due to the domino effect.

An ice storm on March 7, 1990, produced the failure of the Lehigh-Sycamore 345 kV line in central Iowa, damaging a section between towers 51 to 119, with spans from 875 to 1550 feet. A total of 69 structures were affected by the failure with damages ranging from minor stress cracks to support buckling. The failure was contained by dead-end structures at the ends of the affected section. Wipf, Fanous and others at Iowa State University prepared a report analyzing the event for Iowa Power and Light Company [9]. After performing forensic analysis and simulation using finite element analysis, it was determined that the cause of the failure was ice accretion on the conductors, which led to support failure. The mechanics of that failure are important for this thesis because they can shed light on how the sensors will record any failure event when the proposed sensor system is implemented.

In this case, it was concluded that the initiating event occurred because the stress on an insulator fitting at tower 99, due to ice accretion and possibly galloping, was beyond its breaking limit. The exact point of failure appeared to be the fitting point between the isolator assembly and the conductor. The resultant separation of the conductor from the support produced imbalance in the forces at the neighboring structures and posterior collapse by buckling. After that, all the other supports collapsed in a domino pattern due to the imbalance produced in each one as the previous structure failed. Since ice accretion is a progressive event, forces should have been increasing in the conductors and interfaces as the ice build up. A sensor capable of measuring the increase of stress in the conductors or the interfaces, could detect the progressive forces actuating in the couplings. Also, if a dynamic event, such as galloping, appears in the line, sensors could also be capable of detecting the variable forces characteristic of these kinds of events.

A failure involving the same Lehigh-Sycamore 345 kV line occurred on November 1, 1991. This time 114 structures were affected by the failure caused by a storm producing 15 inches of snow and winds up to 60 mph. A similar analysis as before was performed on the failed line [23], and reported the following findings: There were pre-failure conditions in which structures were deflecting due to the combination of ice and wind loads. Either broken wire conditions or an increase of wind and galloping loads caused a plastic hinge in one of the structures of the transmission line, causing it to tilt. Interestingly, the tilted tower didn't fall immediately to the ground thanks to the support offered by two of the three conductors, but after the stresses caused by the added weight were unbearable, the interfaces broke, and the support fell. A domino effect followed and was stopped after the failure of 114 structures by a dead-end three pole support.

The approach utilized by the previously presented analyses was to simulate the conditions leading to the event and compare them to the field observations. The methodology applied relied on static and dynamic analysis on a single structure and on a reduced model of the transmission line using finite element theory.

Taking into account the construction characteristics of a transmission line, combined with the development of a reduced mechanical model of the line to which finite element theory could be applied, a methodology could be developed for optimizing the placement of sensors for tension, stress, strain and vibration in selected points of a transmission line. They also support the feasibility of proposing a *"Mechanical State Estimator"* for the mechanical sensor network, thus providing an approach to detect errors in the measurements collected from the field or even to detect malfunction of individual sensors.

Terrorist attacks on the power system have been occurring in Colombia [1], Russia [24], India [25] and Pakistan [26] among others, causing disruption to the supply of electric energy in wide areas of the corresponding systems. Attempts with more subtle methods have been recorded in 2003 in Western US [27].

In most of the cases in the Colombian transmission infrastructure, the attacks over the system have not been capable of producing generalized blackouts. Even with attacks synchronized in time aimed at different transmission links hundreds of kilometers apart. Only one of such events led to a major blackout of the system. In this incident bombing attacks on three main double circuit transmission lines resulted in the overload of the one remaining link which subsequently tripped and caused a blackout of an entire operating area [1].

When dealing with terrorist groups that exert some amount of control over territory, it can be expected frequent sabotage over transmission assets in or around that zone. In this case, those transmission assets are candidates for placement of appropriate sensors. In other cases, the sabotage actions can be correlated to vectors or axis of mobilization, in which the groups move along a path crossing different transmission assets, in such case a strong correlation can be drawn between the assets being sabotaged and the timing in which their failure occur.

The current methodology for assessing that an attack has been made over a line is to see the operation flags of the distance relays. Given the small likelihood of three phase short circuits in EHV transmission, if a distance relay signals it, it is very likely that a tower have been toppled. Subsequently for making sure, a tryout is ordered and if it is rejected, the line is marked as permanently out of service.

CHAPTER 3. SENSOR SELECTION AND PLACEMENT

Transmission lines are constantly disturbed by the environment, thereby producing stresses and movement in their components. 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.

Currently there are a variety of sensors that can offer the required sensing characteristics. They have been used successfully in specific applications in transmission lines. A survey of those applications will be presented later in this chapter.

Every transmission line is different. They are built over large areas with different terrains and different environmental conditions. This characteristic make the designers apply different kinds of support structures (Steel or wood materials, poles or lattice towers), different designed tensile strength for the conductors and supports and different span lengths. However, some constructive characteristics remain common, such as the use of suspension and strain/dead-end supports. The sensor applications described in this chapter will take into account the common characteristics to propose a general setup for the sensors, without including the details specific to a particular transmission line, such as setting failure thresholds for the variables or the level of relation between them. However, it should be noted that in order to achieve a desired selectivity for the application of sensors to detect mechanical faults on transmission lines, the calibration for the sensors should avoid sending signals of significance when only normal environmental conditions are present.

Mechanical transducer types and principles

For the kind of events required to be sensed by the proposed wireless network setup, sensors for detecting changes in stress, acceleration, angular position and temperature are suggested.

Sensing stress

Stress is defined as the force per unit of area [28], and when applied it can deform an object. The stress can be normal to the surface of the component, or it can be tangential (shear). Forces present in transmission lines conductors are mainly *pure tension*, and are directed outward, normal to the cross section of the conductor [7]. The general expression for normal stress is:

$$\sigma = \frac{F}{a}$$

Where:

σ: *Stress resulting from the application of force F*

F : *Force applied to the element (Tensile Force on the conductor)*

a : *Cross section area of the conductor*

Sensors designed to measure stress rely mainly on the piezoelectric effect. These sensors directly convert mechanical stress into an electrical signal (voltage or frequency), which can be measured by any electrical metering device.

Sensing strain

Bodies subjected to tensile loads experience some level of change in longitude [28]. The resulting stretch or elongation is called strain. The strain per unit of longitude is normally called unit strain. However, the common practice is to use the term strain to refer to the unit strain of an object according to the following relationship:

$$\varepsilon = \frac{\delta}{l}$$

Where:

ε: *Unit Strain on the element (conductor)*

δ: *Total Strain experienced by the conductor*

l : *Overall length of the conductor*

Sensors designed to measure strain rely mainly on the piezoresistive effect. Also called strain gauges, they are measuring elements that convert force, pressure, tension, etc., into an electrical signal. They are the most universally used devices for electrical measurement of mechanical quantities. A strain gauge is a resistive elastic sensor whose resistance is a function of applied strain [29].

Sensing acceleration

Accelerometers are usually referred to as acceleration sensors. They rely on different effects for sensing the rate of change of speed of a body [28]. In its core, the physical phenomenon evaluated is the vibration of a sensing device, felt as periodic oscillatory motion around a reference point. Although some common applications such as shock analysis, linear acceleration or angular acceleration do not involve vibration, the internal design of the sensor rely on it to measure the level of acceleration of the sensed component.

Sensing angular position

The goal of an angular position sensor is to determine the angular displacement of an object in relation to a reference axis [28]. Usually, this kind of sensors does not provide dynamical information, but absolute displacement. When requiring rate of change information, accelerometers can provide the best sensing characteristics [29]. Angular position sensors are also known as *tilt sensors*.

A common tilt sensor is the *inclination detector* or *inclinometer*, which measures the angle from the current direction to the center of the earth and its primary actuating force is gravity.

Sensing temperature

Temperature can be measured directly through contact or by detecting radiated energy [28]. There are sensors specifically designed for each application, and both have intrinsically different measurement principles.

Contact temperature sensors rely on the conduction of heat from the object to the sensing element through an appropriately conditioned interface between them. Thermocouples and resistance temperature detectors (RTD) belong to this category. In the case of non-contact, or radiation sensors, there is no need of physical contact between the object being sensed and the transducer. Infrared thermometers are a common example of these types of sensors and are widely use by maintenance crews for detecting heat related problems in transmission lines (Figure 7).

Previous experiences using sensors in transmission lines

Detecting critical conditions due to the effect of climate and weather on transmission lines have been of research interest since the initial stages of the power transmission industry. Utilities have relied on a variety of efforts to determine and evaluate the mechanical state of transmission lines, mostly in dangerous places through the extension of the line. The use of remote sensing has increased accordingly with the advancing technology. However, those efforts have been oriented towards off-line data recollection or installed at very specific points on the network, and used primarily for maintenance purposes.

A group of researchers of Tohuku Electric Power Co. and Hitachi Cable in Japan installed a remote measurement facility on the 154 kV Hokusei Line [30] for monitoring ice accretion on power lines in mountainous zones. In that particular setup an array of tension, temperature, lightning sensors, TV cameras and current transducers work together to detect and signal ice accretion levels that require attention from maintenance crews. A byproduct of the setup is the availability of more precise fault localization. For transmitting the information collected at each tower, the system uses previously installed composite fiber optic overhead ground wires (OPGW), relaying data from each tower to a central processor installed in the substation. Figure 8 shows the arrangement of the sensors on two towers, and Figure 9 shows the architecture of the complete system.

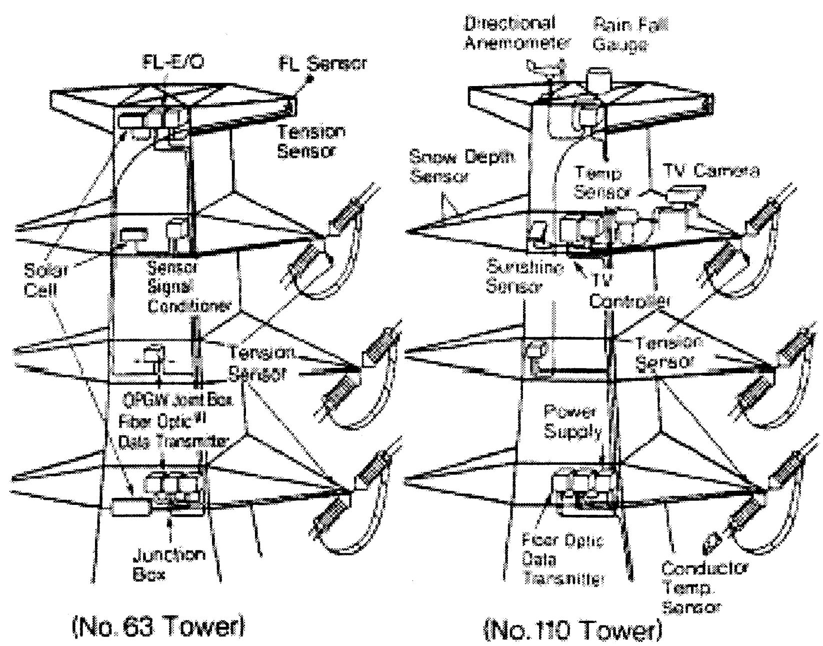


Figure 8. Sensor arrangement in supports for the Hokusei line project

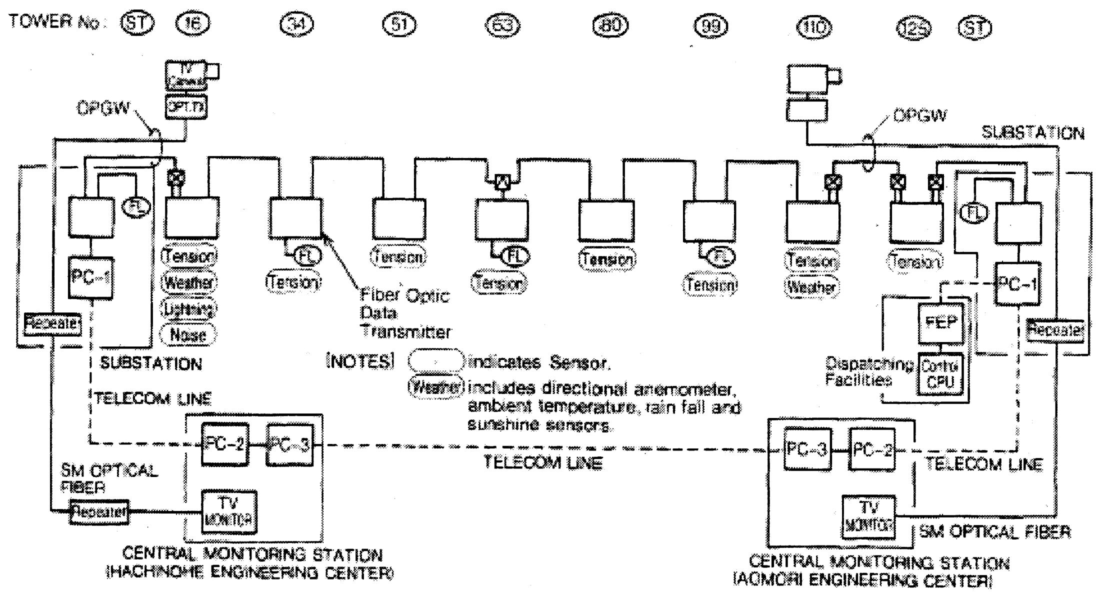


Figure 9. System Architecture of the Hokusei line project

Palazuelos and Fernandez[31] implemented a vibration recording and control method [31], consisting of an accelerometer attached to the ends of the conductor at the point of contact with the retaining clamp. The recording element stores regular measurements of the bending amplitude of the conductor relative to its retaining clamp. The actual monitoring device did not come with communication capabilities; therefore the measurements had to be stored in the equipment memory and later recalled when the monitoring device was removed from the line.

On line monitoring of conductor temperature is a trend that has increased since the establishment of deregulated markets. Mostly it is intended to dynamically evaluate the power transfer capability of the transmission lines optimizing the use of the transmission system by using its entire capacity.

The induction of current in high resistance grounded wire placed in a span at certain distance from the conductors has been proposed as a method for measuring conductor sag and core temperature [32]. It relies on the change of induced current with the distance between phase conductors and the test wire, and indirectly obtains the temperature through calculation of the resulting conductor elongation. A setup like this is suitable for specific, localized application, but could be an expensive option for the objectives of the present work.

A prototype for a real time dynamic system for determining the capacity of a transmission line was implemented by EDM International for the California Energy Commission [33]. It proposes the use of two sensor systems to evaluate the amount of sag a conductor experiences in real time, involving some level of wireless communications. The first system, a pulsed laser distance measurement (LDM) based sensor, utilizes a small, low cost pulsed laser emitter/receiver. It is conceived to be placed in a suitable location along the span to monitor the distance to the ground and calculate sag through the difference of distance from the resting position. The second involves a machine vision system which determines the position of a transmission line with respect to the ground using a passive target attached to the conductor at a fixed distance. Image processing algorithms are used to calculate the movement of the target inside the field of view of the imaging system, thus obtaining the relative distance from a resting position. Figure 10, taken from [33], shows a sketch of the localization of both systems in a particular span.

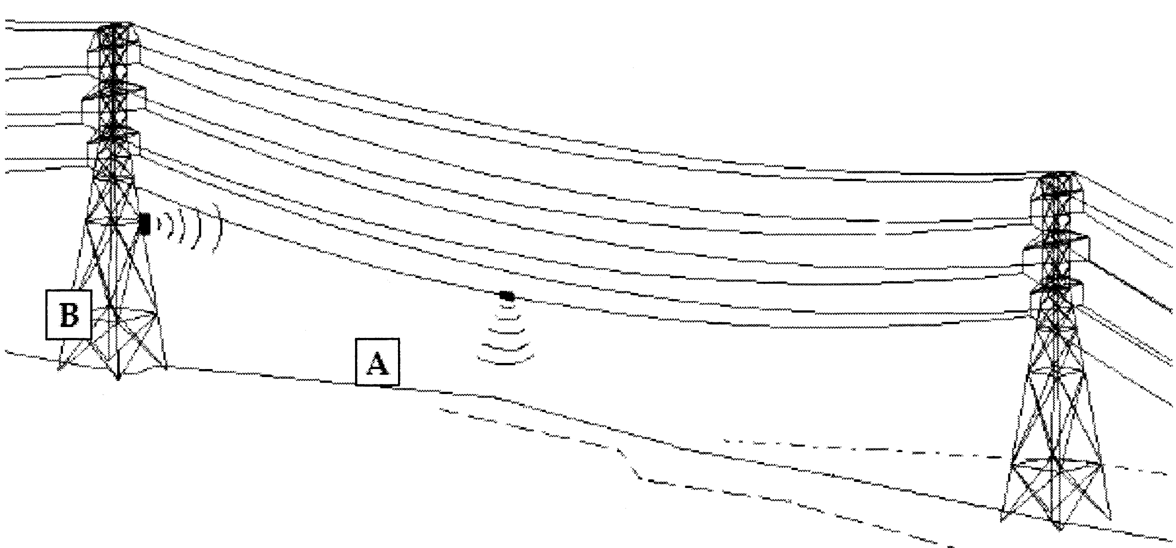


Figure 10. Proposed methods for monitoring sag in Real Time

Proposed sensor selection

The kind of information provided by the sensors is closely related to the structural characteristics of the transmission lines and towers. Since the intention of placing the sensors in the transmission lines is to detect catastrophic events (i.e tower downing due to storms, earthquakes or terrorist actions), proper coordination should be achieved between normal structural stresses and the ones present at failures.

For applications in building structures monitoring, researchers have found that the utilization of acceleration, strain and displacement sensors can provide an appropriate level of observability for earthquakes and wind, as shown in Table 4 [34].

Table 4. Suggested sensor applications for Building Monitoring

Application	*Sensor*
Observation	Acceleration
Experiment	Acceleration, Strain
Structural Control	Acceleration
Health Monitoring	Acceleration, Strain
Damage Detection	Acceleration, Strain, Displacement

The previously presented sensors can also measure the mechanical conditions of the transmission line infrastructure. Although a variety of variables can be measured with the current technology, transmission line support structures have constructive characteristics closely related to building structures, therefore it is proposed here that a similar set of acceleration, strain and displacement sensors can be used to detect actual and potential catastrophic events.

Additionally, given that temperature is also a concern in electric energy transmission; an 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 5. Sensor Application Matrix for a Transmission Line

	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/dead-end 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 Close to 90 degrees	Normal Values
Hot Spots	Normal Values	Normal Values	Normal Values	Isolated high temperature measurement
Overheating	Increased strain caused by sagging	Normal Values	Normal Values	Uniform between conductors and nearby supports

After close analysis of the mechanical characteristics of transmission lines and the effects of the environment, operating point, accidental events and sabotage over them, a sensor application matrix is proposed for monitoring the structural health of a transmission line as a complete body, as shown in Table 5.

It is recommended to apply tension sensors at the interfacing assemblies of all strain/dead-end supports in order to maintain a complete observability of the longitudinal tensile forces acting on the transmission line. This setup has been previously applied with optimal results in the Hokusei line project presented earlier. Foil strain gauges are generally cheaper than tension sensors and have the advantage of being attached directly to the conductor, thus its application is recommended at suspension supports.

Measurements in one support are related to the neighboring support because of the link provided by the conductors, hence, the effect of a mechanical event can be observed farther than the adjacent spans.

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 kind of sensors at different locations, as in the case of strain sensors applied to the conductors at both ends of a suspension interface, or in the case of tension sensors in adjacent structures. Another interesting case is the detection of overheating in the conductors due to overload, in which it is expected that temperature sensors would detect rise in the temperature in the three conductors of the same circuit, and even between adjacent structures; however, if there is a case of an isolated temperature measurement, it is likely because of the occurrence of a hot spot in the line.

Additional cases relate temperature rise in the conductors with an associated increase in sag, therefore producing strain, which can be measured at the conductor attachment points. Wind on the conductors produces increased tension, bending stress and also vibration. Tension produces strain that can be related via the conductor stress-strain diagram.

The dynamics of the events affecting a transmission line plays a fundamental role in the selection of the sensor applications and in the design of the complete sensor system. 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 by weakening the structure can be distinguished if there is a collapsed structure in which previously was not detected any anomaly in the variables.

Most of the monitoring applications have relied on performing sensing at regular intervals of time and saving them on a local memory for later download. There are applications in which, due to the speed of the phenomenon, a significant event may be missed between two scan times. An example is the case of sabotage via a bombing attack. The implementation proposed requires constantly monitoring of the physical quantity being measured and updating every time it detects a significant change.

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 a proposed wireless mechanical sensor network (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 inferred between the output of the electrical protective equipment and the output of the proposed 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 maintenance, or perform 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. The statistical data and the correlation with confirmed faults can also supply the information for calculating failure probabilities.

Other components of the transmission grid can be monitored using sensor technologies. In fact, currently many of them use some kind of sensor application for protective duties. Transformers contain pressure and temperature sensors. A proposed application matrix is presented in Table 6.

Table 6. Sensor application matrix for power systems

Quantity	***Transmission Lines***	***Substations***	***Transformers***	***Circuit Breakers***
Acceleration	X			
Vibration	X	X	X	
Stress/Strain	X			
Tension	X			
Shock	X	X		
Pressure			X	
Temperature	X	X	X	X
Inclination/Tilt	X	X	X	
Position				X
Protection Relay Output	X	X	X	X

Proposed sensor placement

The selection of sensors proposed in the previous section guides the choice of locations within a support on which to place them.

Regular tension or strain sensors can be mounted at the interfaces of strain/dead-end supports. It is recommended to install them at all the conductor attachments of all strain/dead-end structures because of their important role in maintaining the physical integrity of the transmission line. This can result 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.

However, 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. Since there is no complete longitudinal force transfer between the conductors and suspension supports interfaces, the appropriate sensor to use is a foil strain gauge affixed to the conductors close to the point of attachment to the interface. A first approach to the optimization of strain sensing capabilities on suspension supports is to place them on both sides of the point of attachment of the conductors every third tower as shown in Figure 11 using a top down view. In this manner, each support monitors only one phase conductor, but the system do not loose observability because each attachment point not being monitored directly, is monitored by an adjacent support.

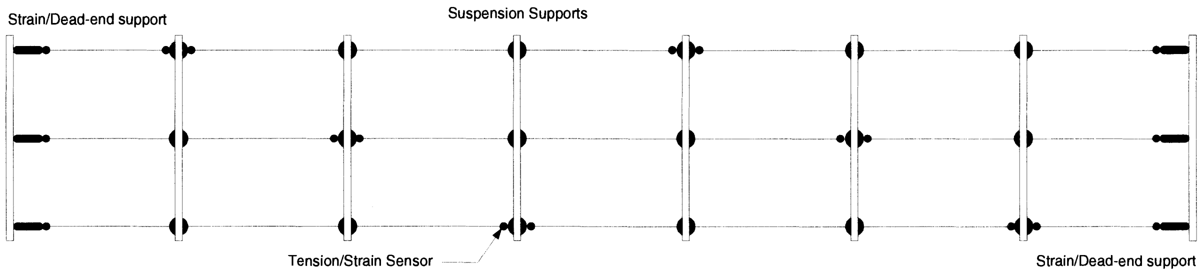


Figure 11. Tension/Strain monitoring on suspension supports

Tension sensors applied to strain and dead-end supports have no high voltage isolation problems, since they can be placed in the insulator arrangement [30]. Tension sensors applied at suspension supports have to be placed directly into the conductor, therefore involving problems with the insulation levels if a regular wired data link needs to be used; this offers a very good reason to use smart wireless sensors for this application since the communication will be provided via the wireless link.

Vibration and tilt sensing is often provided by accelerometers. It is proposed to install one in the support body to detect vibration and tilt in the structure 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 overload detection 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 determinant factor for selecting the complete application for hot spots.

Figure 12 presents the overview of the sensor placement proposed in this chapter.

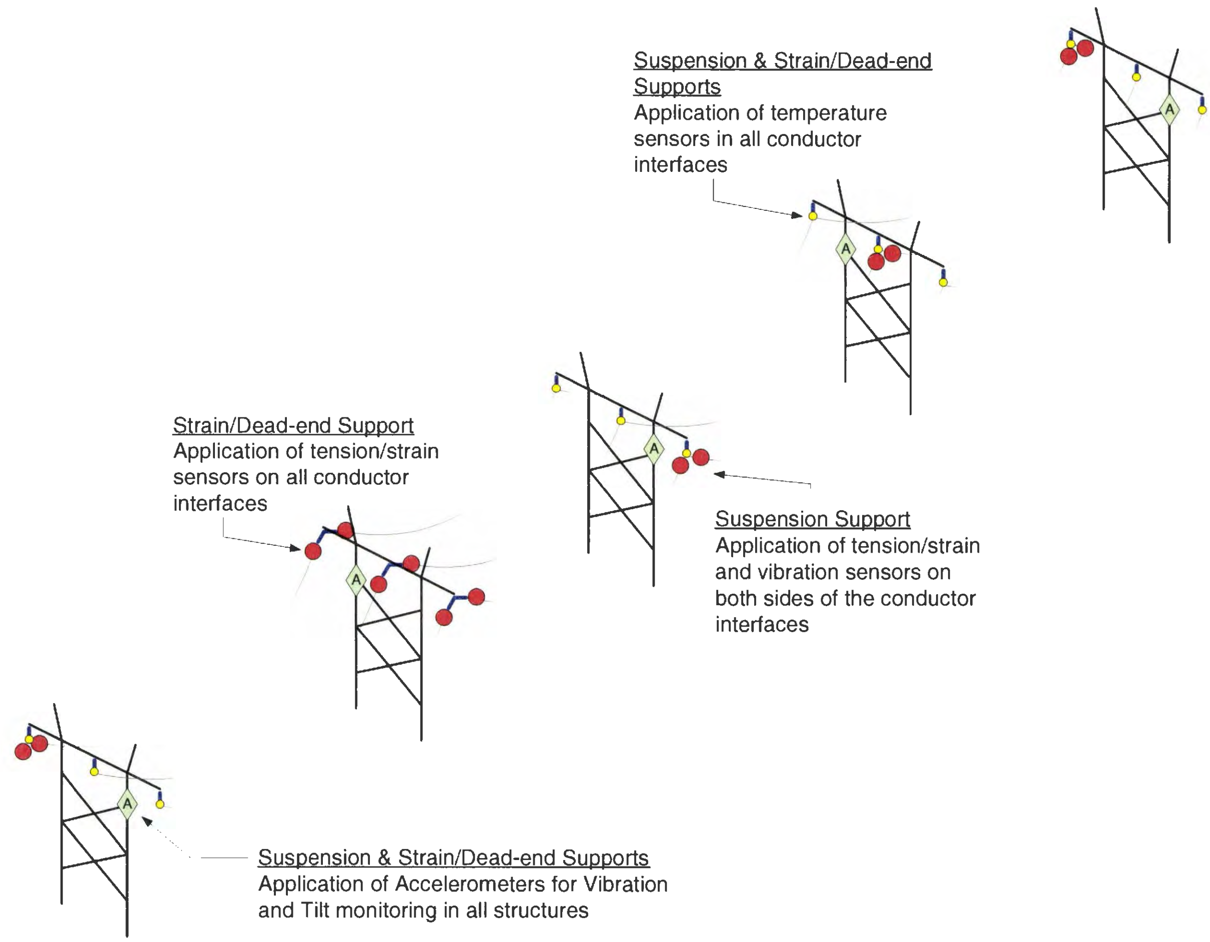


Figure 12. Overview of the sensor placement recommendation

CHAPTER 4. THE WIRELESS MECHANICAL SENSOR NETWORK

Wireless sensor networks are a relatively new technology, appearing as the combination of various other technologies established for a long time. The trigger for the widespread use of wireless sensor networks has been the advance of wireless communication and electronics micro-integration. The practical consequence of these advances is the availability of low cost systems to provide sensing and communication capabilities in one single package. In fact, a number of applications that usually relied on wired communications for collecting data from sensors in the fields, now use wireless sensor networks because of the reduce cost of implementation and maintenance [34].

In the structural monitoring field, the use of sensors to monitor the response of bridges have been extensively applied since 1977, instrumenting 61 long span bridges in the United States [35]. Sensors have been localized in particular places in the structures and the collection of data was done via wired connection to a central data processor. Now, researchers are using wireless sensor technology for obtaining structural health monitoring data. Kurata, Spencer and Ruiz-Sandoval [34] proposed the use of the *Berkeley Mote* platform for vibration and strain monitoring in civil structures. Lynch, Sundajaran and others [35], propose to take advantage of the limited computational power available in each smart sensor of a wireless sensor network to perform localized structural health assessment. The advantage of this approach is the reduction of the traffic in the communication channel and the ability of each sensor to continually assess the performance of the monitored variable for the identification of damage.

Previous monitoring applications on transmission lines have made use of wired communications for sending the signals to a central location, taking advantage of the increasing trend of installing fiber optic ground wires (OPGW) in the transmission lines [30]. A drawback of the previous implementation is the requirement that each transmission line should have an optical fiber ground wire installed which is not the case in all lines and also involves high installation and operating cost to implement. Additionally, each support with sensing capabilities should have a fiber optics interface for coupling the electrical sensor signals to optical signals, incrementing the costs and making more difficult the installation. An advantage is the high bandwidth associated with the use of fiber optics.

Irrespective of the selection of the type of communications link between supports (wired or wireless), there is still the problem of relaying the signals from the sensors installed in the structures, interfaces and conductors to the collecting central unit in each support. Again, wired connectivity can be used for some of the sensing units, but it involves running signal cabling through the structures with the associated costs of installation.

In this chapter a conceptual design for the architecture of a *Wireless Mechanical Sensor Network (WMSN)* for transmission lines using wireless links between the sensors and the central processors in each support, and between central processors in different structures will be proposed. This approach takes advantage of the low cost and ease of installation of the system and the ability to work without the need for additional communication infrastructure.

Characteristics of a wireless sensor network

The concept of a wireless sensor network involves the combination of sensing, data processing and communications capabilities in just one piece of equipment small enough to be cheap and efficiently installed, covering large networks of those sensing nodes that can monitor the overall behavior of a physical environment. The original concept calls for the deployment of a large number of sensors in which their localization is not known previously and let them establish optimal network topologies to communicate the status of the monitored system to a central processor or *sink.*

The hardware of a wireless sensor network node consists of sensing devices, analog to digital converters, a microprocessor, data storage, a data communications device and a power source, as shown in Figure 13. Actual technology has permitted the integration of almost all of this functionality in a small package with low power requirements, permitting the deployment of sensor nodes for virtually undefined periods of time.

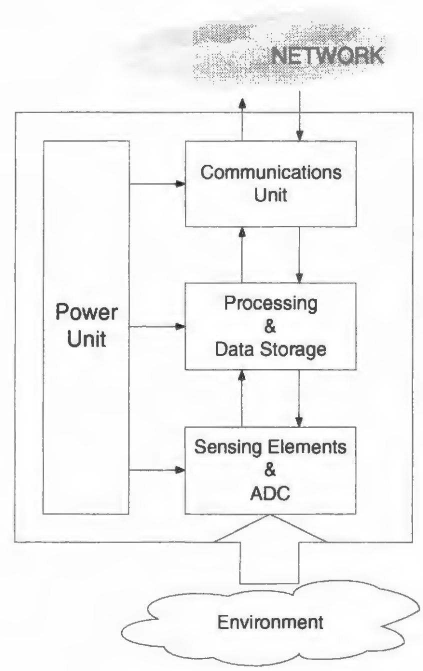


Figure 13. Wireless Sensor Node Hardware

The ability to integrate locally the sensing and data processing functionality provides any node with the capability to avoid the transmission of large amounts of monitored data. Instead, local processing can perform analog to digital conversion, signal conditioning and analysis, convert raw information to numerical engineering values, detect anomalies and even obtain modes of oscillation for a determined structure. Thus, communication bandwidth utilization is required just when the node determines that the information obtained from the environment is worth being transmitted, or when it is interrogated by the central processor or any other node.

The communication capabilities of each sensor node enable it to communicate with others via a wireless medium. However, given the power consumption and size constraints, there is a limit on the transmission range. Most applications do not exceed 500 feet, while tens of feet are a typical unit of measurement [37]. The conceptual design establishes that for covering long distances, the wireless sensor network must route the information through a series of *hops* between deployed nodes. In combination with range limitations, bandwidth presents another constraint for data transmission in wireless sensor networks. A tradeoff exists between the amount of exchanged information and the speed of their exchange because of this constraint.

The combination of communication and processing functionality allows the sensor network to achieve collaborative computing, using the processing power of a varied group of sensors. The result of such collaboration is the construction of a complete image of the status of the monitored environment with little or no intervention from a central processor.

Power management is one of the main technological concerns related to wireless sensor networks. The wireless characteristic of this kind of networks, in combination with the requirement for the sensor nodes to operate without intervention for large periods of time makes power supply and energy conservation an important topic. In addition, the small size of sensor nodes limits the amount of energy that can be supplied to it given that it also limits the size of the power source. The power requirements for a sensor node are driven by the amount of processing expected, the frequency of operation and the communications functionality. In fact, communication is one of the most energy consuming operations for a sensor node, with each bit costing as much energy as 1000 processing instructions [37].

Different options exist for supplying energy to the sensor nodes. The most common method is the use of long life batteries which can provide energy for extended periods of time to low power consuming sensor nodes. Another popular method is the utilization of solar cells to charge rechargeable batteries on the sensors. More promising for the application proposed in this thesis work are the methods for harvesting energy from the environment in which the sensors would be installed.

Electric energy can be collected by magnetic induction, thanks to the fact that energized conductors are available close to the appliances. This method was employed by EDM International for the real time monitoring of overhead lines proposal in California using commercially available inductive power sources [33].

Another feasible method relies on the application of the piezoelectric effect for harvesting electric energy from vibration or strain [39], which makes it ideal for sensing units placed on conductors.

The utilization of a combination of the previously proposed methods and rechargeable batteries for backup power can guarantee long life deployments of sensing units with practically no need for maintenance.

Proposed architecture for a transmission line WMSN

The concept of a wireless sensor network envisions the deployment of a large number of sensing units disregarding their localization. This is not the case for the application proposed in this thesis work. For the recommended implementation of a *wireless mechanical sensor network* for transmission lines, the localization of each node is determined in the pre-deployment phase, with sensors of particular characteristics placed in predefined places along the support structures and conductors. Thus, complex routing algorithms are not required for the nodes in this application.

It is proposed that communication between structures occur via wireless linkage; even when having the opportunity to rely on wired communications through fiber optics as discussed in the introduction of this chapter. Wireless communication between towers is recommended because it could provide 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 acts of sabotage). It has been shown previously that the implementation of wireless communication between towers could also reduce the costs of installation and maintenance of the complete wireless mechanical sensor network.

The proposal of the architecture for the wireless mechanical sensor network takes into account the previously mentioned topics, additional constraints caused by the characteristics of the transmission lines and also the particular requirements established by the design of the application.

In order to assess the overall mechanical and electrical condition of the transmission infrastructure, a central processor in the energy control center should obtain the information from the sensor networks installed in different transmission lines. This can easily be achieved by taking advantage of the current installed communications infrastructure between the substations and the energy control center. The proposal in this thesis is to include the messages originated from the WMSN with the electrical data currently being collected by the RTU in each substation, thus, guaranteeing its delivery to the control center via SCADA.

Each substation will count on a *local substation processor (LSP)* for the information received from the WMSN at the transmission lines connected to it. The purpose of the processor is to handle the different modes of operation of the WMSN, execute message processing; and perform data validation and analysis.

The inherent lineal characteristic of a transmission line drives the overall topology of the sensor network. Communications between nodes in such a topology are reduced to their adjacent node and at most two hops ahead (communications range permitting). Substations at the end point of the transmission line will have direct communication with the first (and second) adjacent structure. 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 overall architecture for the WMSN is shown in Figure 14.

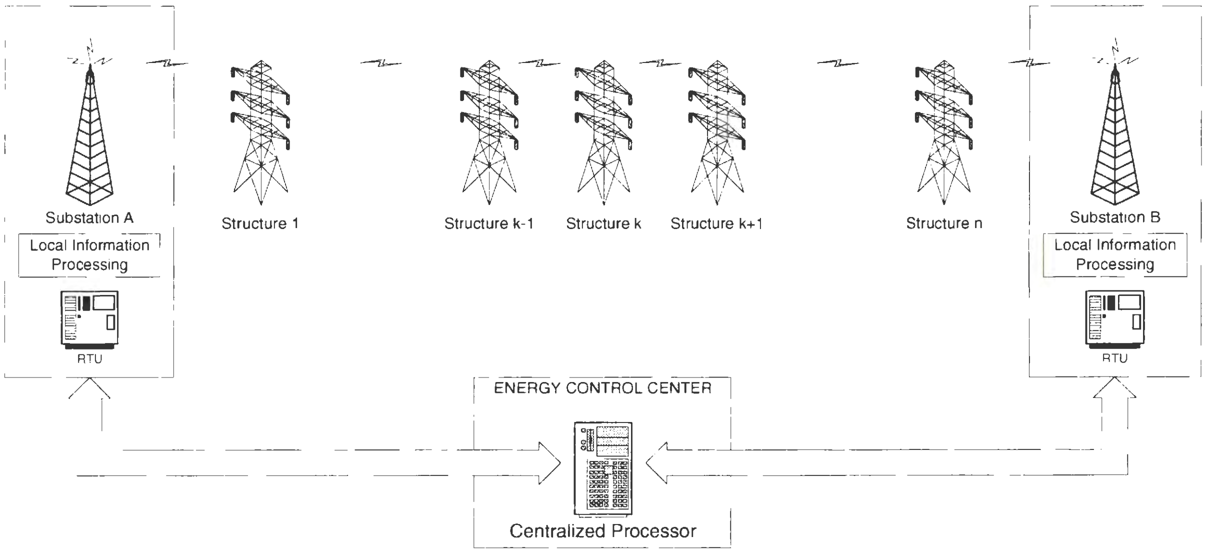


Figure 14. Overall architecture of the WMSN System

The two layers model

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 the smart sensors is not very long and extending it is not efficient due to power supply limitations.

A two layers model is proposed to overcome the restrictions imposed by the range/energy management issue on the sensor nodes. By providing a *local data & communications processor (LDCP)* on top of each support, the sensor nodes installed there could communicate with it, forming a *local sensor group (LSG)* with required communication ranges not greater than 100 feet given the dimensions of typical transmission line supports (Figure 2). 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 in Chapter 3. Therefore, some data cross checking and structure health assessment can be done locally on each tower. Sensors on the LSG and the corresponding LDCP form the Layer 1 of the WMSN. It should be noted that there will be multiple instances of the Layer 1, one at each support.

Support to support communications and collaboration rely on the LDCP on top of the structure. The interaction between all the LDCPs on the supports is the basis for the Layer 2 of the WMSN and forms the *inter-support communications and collaboration (ISCC)* Layer. In this layer all the message processing and transmission required for delivering the mechanical status information to the substation occurs. Figure 15 shows the conceptual two layers model depicting two adjacent structures.

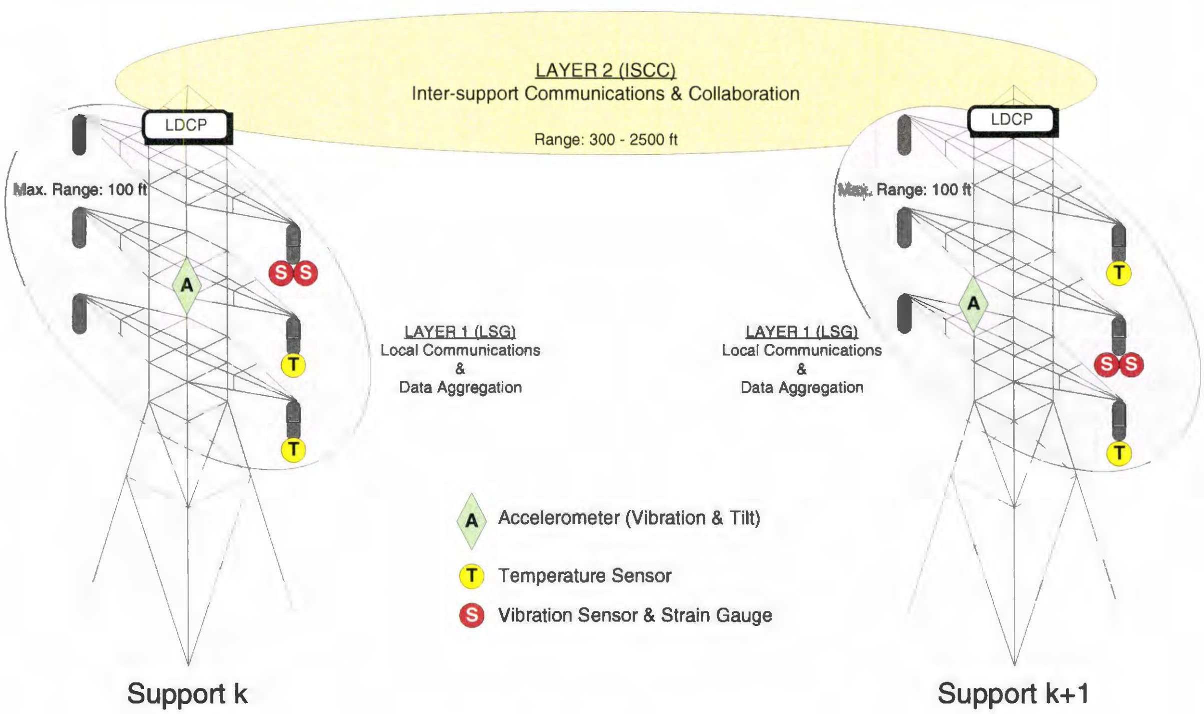


Figure 15. Two Layers Model

An advantage of implementing a local data and communications processor (LDCP) on each structure is that it can avoid the range limitations of the sensor nodes. Its radio can achieve a larger range and count with an increased communications bandwidth due to the fact that it do not have size and power constraints. For that matter, it can harvest power from an inductive source placed near the closest phase conductor and can also count with a bigger rechargeable battery. The normal range expected for the application varies from 300 to 1500 feet, using more powerful radios in particular structures where longer spans (up to 3000 ft) exist for special crossings.

Time response characteristics and requirements

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 [3]. 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 – 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 will not be required to provide principal or backup protective functionality.

In the lower bound of the time requirements appear the SCADA (Supervisory Control and Data Acquisition) system which will be discussed in the following chapter. It collects information from the substations typically every 4 seconds. Therefore, it would be desirable that the *local substation processor (LSP)* at the substation achieve at most one overall diagnostic of its supervised lines for every SCADA cycle.

Given the latter requisites, it is expected that the total time 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.

The total time for message delivery can be calculated with the following formulation:

$$t_{line} = (t_{hop} + t_{proc}) \cdot n_{hop}$$

Where:

t_{line} : *Total time from transmitting a message from one end of the line to the other*

t_{hop} : *Time required for a message to travel one hop (support to support)*

t_{proc} : *Processing time at each LDCP at the supports*

n_{hop} : *Number of hops on the line*

And:

$$t_{hop} = \frac{l_{msg}}{r}$$

Where:

l_{msg} : *Message Length*

r : *Communications bandwidth*

Given that there are some variables in the previous formulation that can be manipulated and others that are not, some important conclusions can be drawn. The number of hops is fixed, and it is directly related to the number of support structures in the line. The processing time is commonly various orders of magnitude inferior to the hop time given the actual speeds of mainstream microprocessors. Thus, the hop time is the driving variable for obtaining proper communication times. At the same time, the hop time is the result of the amount of bandwidth used by the message. Therefore, by establishing a proper ratio between the size of the message and the available communications bandwidth, the transmission time requirements could be achieved.

Operating modes

In this work, a method is proposed to enable collaboration between LDCPs in adjacent supports as well as collecting data 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 wireless mechanical sensor network.

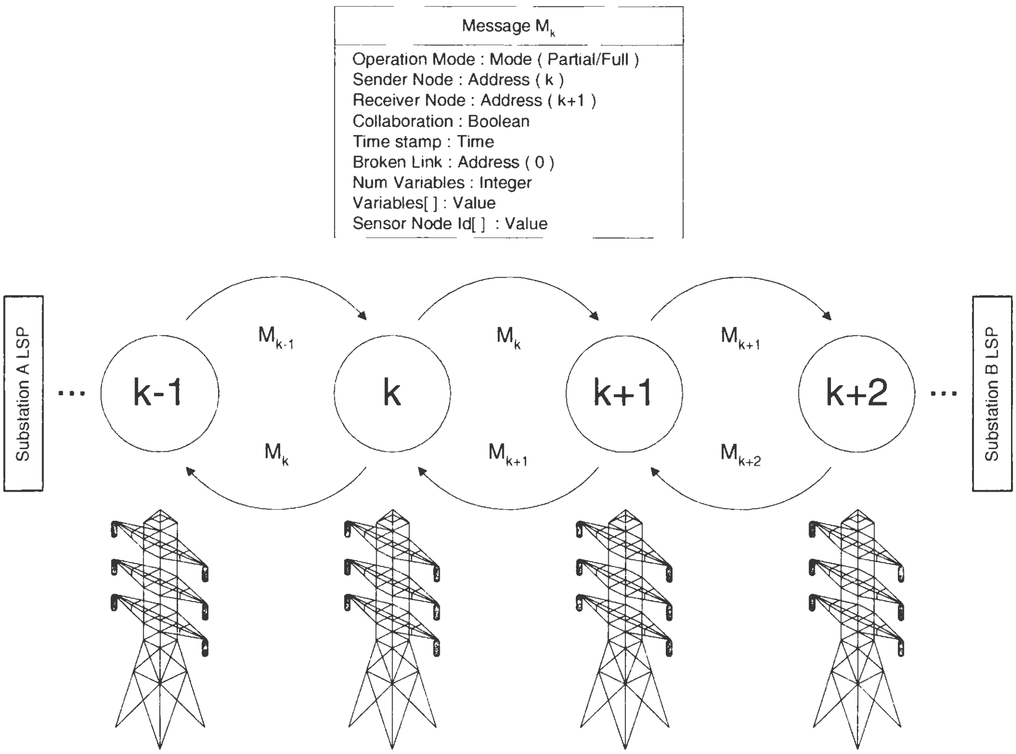


Figure 16. Message broadcasting

Both modes rely on the sequential transmission of status messages by the LDCP in each support. In the proposed operating principle, a trigger LSP in one substation commands the start of a *data collection sweep* across the transmission line, interrogating the first LDCP (mounted in support 1, as shown in Figure 14). 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. Figure 16 presents the proposed message contents. Directionality is achieved by including the sender and receiver address in the message header. This way, when substation A in the far left 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 one, setting 1 as the sending and 2 as the receiving addresses. This process will continue until the sweep reaches the substation B LSP. Then, LSP_B will trigger 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 will contain one vector of data values and another with 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.

Partial (Fast) Mode: In the partial mode, messages exchanged by the LDCPs contain only a reduced set of the total data present on every LSG. As an example, the set can contain all the sensing information from the previous LDCP and the maximum value of each variable group (vibration, strain and temperature) accompanied with its associated sensor localization. In consequence, the size of the message will be small enough to provide high communication speeds. In this manner, various complete line sweeps could be executed within one SCADA cycle.

When the message reaches the next LDCP, it will compare the values on the message with its own variables in the LSG. If there is some degree of concordance, the LDCP will select for transmission the maximum between its own variables and the ones in the message. If there is a notorious discordance, it will request a data collaboration session with the previous LDCP for validity checking using the expected relation between sensor information. If the cross validation for tension/strain and vibration in the conductors fail, it is a signal of possible bad data, and a *full mode sweep* should be requested, inducing complete validation at the LSP. If the validation for temperature fails it can signal the presence of a hot spot.

The data collaboration session is implemented by establishing a local peer to peer, full data exchange of the variables in each LSG.

Full (Slow) Mode: The full mode collects the status information from all the sensors in the transmission line, enabling the *local substation processor (LSP)* to obtain a complete picture of the mechanical status of the line. Since the message size on this mode is bigger than in the partial mode, bandwidth utilization is also larger. For that reason, it should be expected that end to end transmission times increment various order of magnitude above the transmission time of the partial mode.

The reason for collecting all the sensor data from the field with the full mode of operation is to provide the local substation processor (LSP) with a complete picture of the mechanical health of the transmission line. With it, the LSP can execute verification algorithms oriented to detect any inconsistencies within the collected data. The previously proposed *"Mechanical State Estimator"* for transmission lines could be the algorithm of choice.

Failure detection of any LDCP is provided by means of implementing a timeout function in the preceding LDCP and using it as follows:

- When starting a data collection sweep, the initiating substation will place its address (0 or *n+1*) in the broken link field of the message.
- $LDCP_{k-1}$ broadcast a message to $LDCP_k$ by placing *k-1* in the sender node field of the message and *k* as the receiving node. At the same time, it starts a timeout clock.
- The message from $LDCP_{k-1}$ reach $LDCP_k$ and it then executes the local process and broadcast the modified message setting *k* as the sending node and *k+1* as the receiving node.

- Since the broadcast is not directional, $LDCP_{k-1}$ will receive an instance of the message from $LDCP_k$ to $LDCP_{k+1}$.
- If the message from $LDCP_k$ to $LDCP_{k+1}$ is received by $LDCP_{k-1}$ within the established timeout time, it will stop the clock and wait until a new processing request arrives.
- If the message does not arrive in the time set, $LDCP_{k-1}$ will mark node k as a broken link (setting k as the address in the broken link field of the message), and reversing the direction of the sweep by sending to $LDCP_{k-2}$ a copy of the last message broadcasted to $LDCP_k$.

In this way, when a LSP receives a return message with an address different from zero or *n+1* in the broken link field, it will know that there is a failure in the referenced node. Then, the centralized processor would receive concurrent notification from substations A and B about a broken link in the communication path. 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.

Having complete observation of the entire line, the LSP can perform more extensive analyses about the health status of the line. As a result, the *local substation processor* (LSP) can determine the mechanical status of the line, and classify it as one of the four proposed possible conditions:

- Normal
- Suspicious
- Imminent
- Fault

The proposed conditions will be discussed in Chapter 6 when dealing with the different mechanical/electrical failure modes expected to be present at any time in a particular transmission line.

Another operation mode could be implemented using the same operation principle and message structure. In this case an exception driven transmission is proposed, in which, when a determined LDCP registers a significant change (above or below predetermined thresholds) in any of its monitored variables, it will broadcast a new message in both directions. Then, since the LSP in each substation maintains a virtual model of the transmission line and all of the LDCP and LSG, it can evaluate the mechanical health conditions of the transmission line at any moment from the received messages from all the broadcasting nodes. A drawback of this approach is that when there is a damaged node, it will not be noticed directly by the LSP, because there is no transmission being broadcasted from it, therefore, regular interrogation will still be needed for failure control. A combination of the proposed operation modes could be implemented for taking advantage of the benefits provided from each approach.

CHAPTER 5. THE ENERGY MANAGEMENT SYSTEM SIMULATOR

The *energy management system* (*EMS*) is the core of every power system control center. These hardware and software packages collect operational data from all the substations in the power system, filter the measurements for bad data or communications errors and present the operator with a set of tools using this refined data. This enables the operator to perform analysis on the current state of the power system and determine its future behavior.

In order to evaluate the feasibility of using the information from the WMSN for providing recommendations in real time to the operators in the control center, it was desired to use a simulator for the operation of the power system in real time. The *dispatcher training simulator* (DTS), or e-terra Simulator, from Areva T&D provides this functionality. The *e-terra simulator* emulates the SCADA/EMS system with no difference with the actual tools in any control center, as a result, providing a complete electrical picture of the simulated power system in real time. References [42] – [46] provide the complete documentation of the Areva EMS and DTS systems. An abridged version will be presented in this chapter for completeness.

The e-terra SCADA subsystem

The basic functionality of the EMS system is provided by the *e-terra SCADA* subsystem, managing the data acquisition and supervisory control capabilities for real-time monitoring and control of the power system. It gathers the power system's state variables from the field and presents them to the operators through one-line and tabular displays. The SCADA subsystem also enables operators to control devices in the field from the control center.

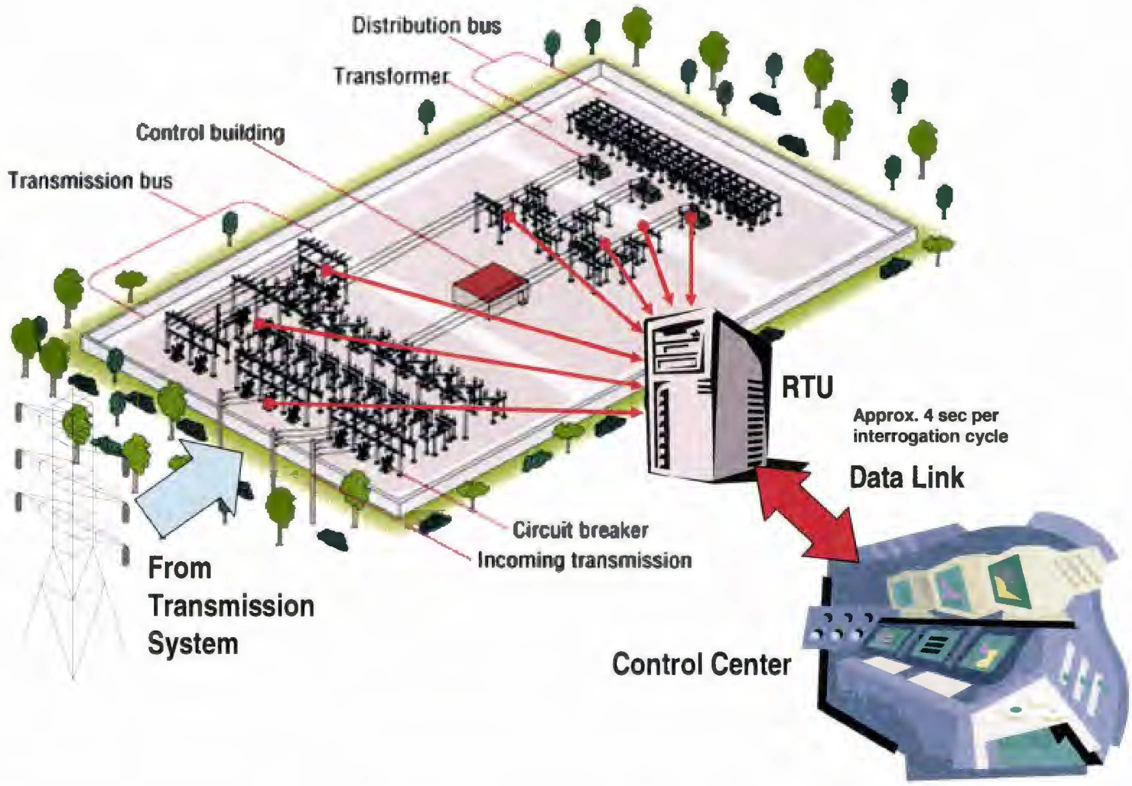


Figure 17. Substation data collection

In the field, every substation includes a *remote terminal unit* (RTU) which collects the state variables of the power system in the substation level at any given point in time as shown in Figure 17. The collected variables are:

- Bus voltages.
- Active and reactive power flows.
- Circuit breaker and disconnector status (open/close).
- Transformer taps positions.
- Protection devices operating flags.

The data collected is then relayed at predetermined intervals (usually 4 seconds) to the SCADA processor in the control center through the communication structure provided by the system. Once it reaches the SCADA processor, the data undergo standard validation functions including quality and limit checking, alarming and calculation triggering. Then, it is stored in the real-time SCADA database.

The SCADA database maintains an up-to-date picture of the monitored system which allows real-time observation of the state of monitored devices using the tabular or one-line displays. In the e-terra platform, the SCADA database is called SCADAMOM. The data collected by the RTUs is classified as one of the three major types of power system information that the database can hold:

- <u>Analog Values</u>: are numeric values representing the state of variable-state devices, such as power lines, transformers, generating units, etc. Once they are retrieved from the RTU, they are converted, checked against reasonably limits and placed in the database. The value is then compared against operative limits, generating alarms when violated. Analog values are stored in ANALOG records in the database.

- <u>Status Values</u>: represent the state of discrete-state devices, such as circuit breakers, disconnectors, tap changers, etc. The status values can be simple on/off or open/close inputs or a combination of inputs from a three-state device. When status changes are detected, alarms are generated if appropriate. Status values are stored in POINT records within the SCADAMOM database.

- <u>Count Values</u>: are values originated in pulse accumulators. They are often used to measure the total amount of energy (MWh), liquid or gas that has passed by a specific location of the monitored system in a determined period of time. Count values are stored in COUNT records in the database.

The supervisory control capabilities enable the operation of power system devices in the field. Operations like open or close a circuit breaker, change the tap position of a transformer or change control set points are among the mostly used in practice.

The e-terra SCADA subsystem supports receiving data from the e-terra simulator instead of the RTUs from the field. It then processes the data and makes it available to the SCADAMOM clients. The e-terra SCADA handles control requests issued from the e-terra simulator in a special manner also, thus, the e-terra simulator can simulate changes to the system in a closed loop fashion.

The e-terra Generation subsystem

The e-terra Generation Subsystem provides functionality for managing the generation associated with the control areas monitored by the EMS system. It consists of real-time and study functions. The real-time functions include automatic generation control (AGC), transaction scheduling and load forecasting. The study functions permit conducting economic dispatch and short term transactions (Economy-A) analysis.

The real-time functions are provided by the RTGEN application of the EMS system. It allows the operator to monitor, analyze and control real-time generation within a control area, or within multiple control areas.

The principal function of RTGEN is automatic generation control (AGC). The automatic generation control is a closed-loop control algorithm that provides generation control based on three major objectives [48]:

- Maintain the system frequency inside a small band around the specified nominal value (60Hz).
- Maintain the established values for the power interchanges between control areas.
- Maintain each unit's generation at the most economic value.

In order to achieve the proposed goals, the AGC determines the appropriate changes in the generation based on the current frequency, load and interchange conditions and sends control pulses to the local plant controllers, commanding the increase or decrease of power generation. This process is executed periodically, usually every 8 seconds.

The e-terra Transmission subsystem

The e-terra Transmission subsystem provides applications supporting real-time and study mode network analysis for determining the state of a power system network, its level of security and how the level of security and economics of the network can be improved. The mostly used components included in the transmission subsystem are:

- Real Time network analysis (Topology processing and state estimation).
- Contingency analysis.
- Security enhancement algorithms (Constrained dispatch, contingency planning and preventive action).
- Short circuit analysis.
- Voltage – Reactive power dispatch.
- Power flow and Optimal power flow.
- Outage scheduler.
- Transfer limits calculation.

The e-terra Simulator subsystem

The e-terra Simulator provides an off line representation of the monitored power system that can be used to simulate its real time operation and control in the energy control center. It uses the same interfaces and is composed of much of the same software as the real-time EMS. It is originally intended for supplying a realistic environment to system dispatchers in training for practicing various operating tasks under both normal and emergency conditions. For this thesis, the e-terra simulator is used for providing real-time simulation of the power system as a test bed for the integration of mechanical health information from the WMSN. Figure 18 presents a depiction, taken from [46], of the e-terra Simulator functionality and components.

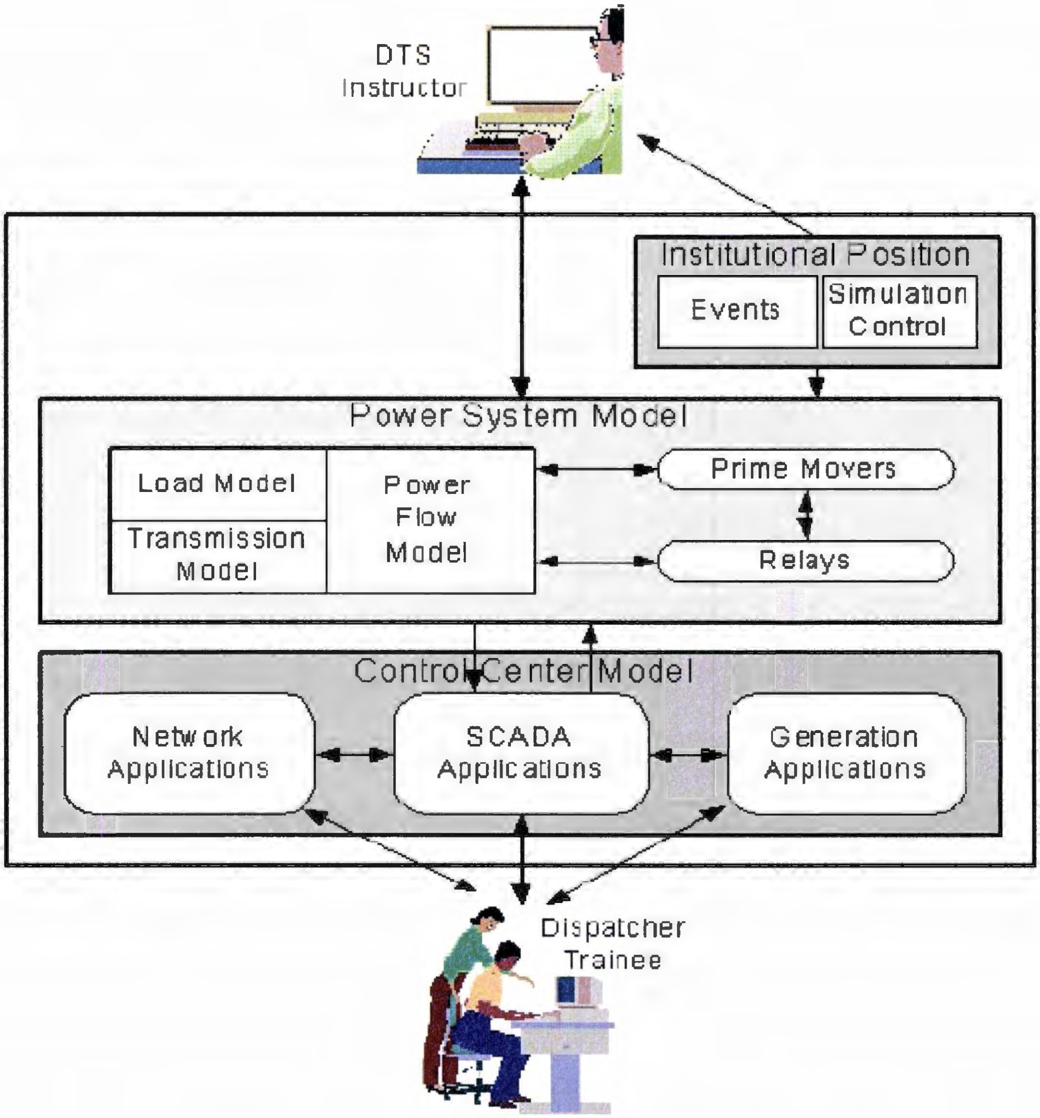


Figure 18. e-terra Simulator functionality and components

The e-terra simulator uses a power system dynamical model to create a simulated operating environment. The model contains a detailed description of the components and topology of the system; and a set of schedules for modeling the future status of energy transactions, generation, loads, and circuit breakers. The state of the transmission system is calculated by successive Newton's method power flows, usually every 2 to 8 seconds, and their results are used to update the SCADAMOM database after each iteration. IEEE standard long term dynamics models are used to simulate the dynamic behavior of the generating units' prime movers. Thus, transient responses and inter-machine oscillations are not modeled. The e-terra simulator also includes protection relay models for simulating the action of over current, over/under voltage, over/under frequency and synchro-check relays.

The e-terra PC Link

The e-terra PC link is a tool provided by the e-terra Habitat environment of the AREVA EMS that enables communication between the EMS/DTS databases and external applications running under Microsoft Windows. This functionality is provided by the dynamic data exchange (DDE) service of windows through the execution of the HABDDE program of the AREVA platform. Complete information about the e-terra PC link can be found in [47].

The IPSS software build as part of this thesis work makes use of the Windows DDE service for exchanging information with the e-terra PC Link tool in real time.

The EMP60 test system

The e-terra platform provides a 60 buses test system which contains all the information required to properly execute the e-terra simulator. The data is stored in databases containing the network topology (NETMOM), the SCADA model (SCADAMOM), the Generation model (GENMOM) and the DTS model (DTSMOM). The EMP60 model was used for power system simulation purposes in this thesis work. The system includes complete substations and generation plants configuration. For analysis purposes, a simplified representation of the EMP60 test system was developed and is show in Figure 19.

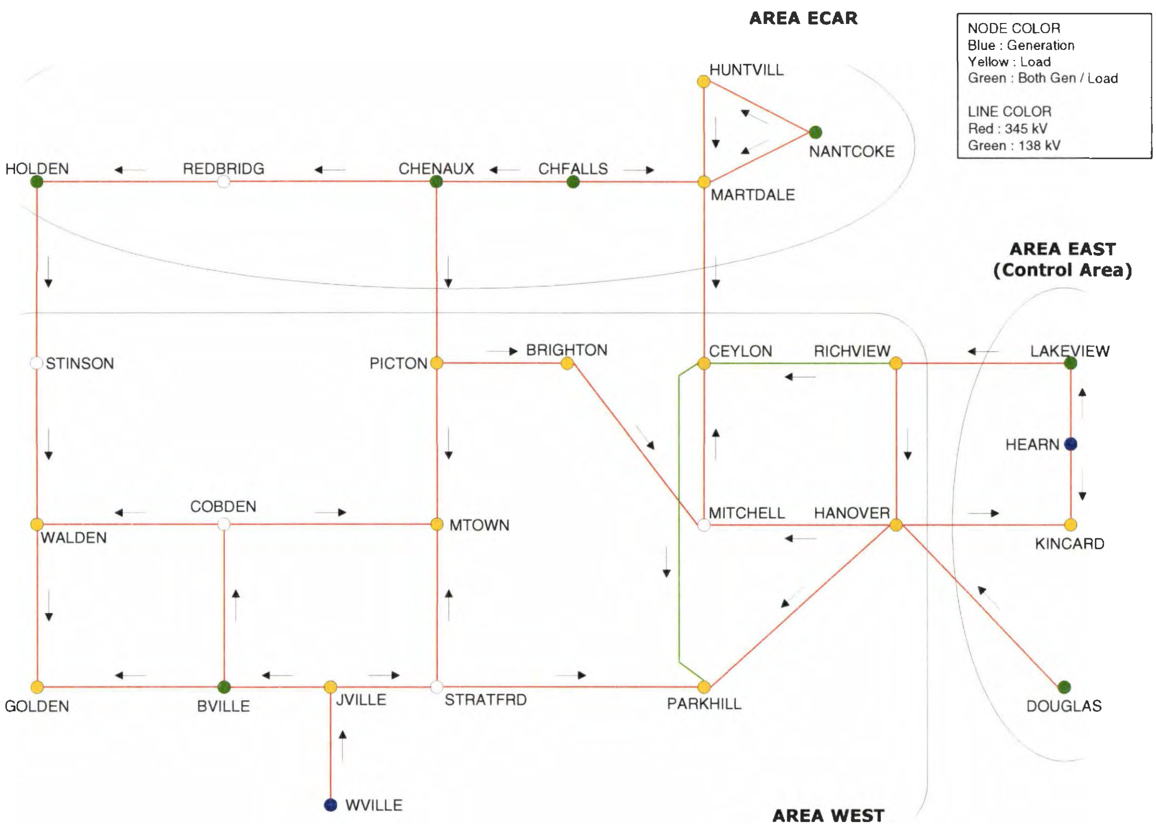


Figure 19. The EMP60 test system

The test system consist of three control areas: EAST, WEST and ECAR, of which, area EAST has been designed as the main control area. The system has a peak load of 6,100 MW and generation capacity of 10,865 MW. The load profile of each area is shown in Table 7.

Table 7. Load profile for the EMP60 model

Area	*Minimum Load [MW]*	*Maximum Load [MW]*
EAST	612	919
WEST	2209	3244
ECAR	1165	1947
Total Load	3986	6110

The generation units and plant controllers associated with each operating area are shown in Table 8.

Table 8. Generation resources in the EMP60 model

Control Area	*Plant*	*Unit*	*MVA Rated*	*Minimum MW*	*Maximum MW*
EAST	DOUGLAS_31:CT1_CCYC	DOUGLAS:CT1_COMB_CYC	50	10	50
	DOUGLAS_31:CT2_CCYC	DOUGLAS:CT2_COMB_CYC	50	10	50
	DOUGLAS_31:DB-A	DOUGLAS:G1	800	50	1000
	DOUGLAS_31:DB-B	DOUGLAS:G2	800	50	700
	DOUGLAS_31:ST_CCYC	DOUGLAS:ST_COMB_CYC	40	10	40
	HEARN___31:HRN1	HEARN:G1	600	50	500
		HEARN:G2	600	50	500
	LAKEVIEW31:LV1_CONTROLLER	LAKEVIEW:GEN1_GENERATOR	800	50	700
WEST	BVILLE__31:BV1	BVILLE:1	900	0	825
	WVILLE__31:WV1	WVILLE:1	1000	50	925
ECAR	CHENAUX_31:CHX1	CHENAUX:1	1300	50	1100
	CHFALLS_31:CF1	CHFALLS:1	800	50	700
		CHFALLS:2	900	0	825
	HOLDEN__31:HD1	HOLDEN:1	2200	50	2000
	NANTCOKE31:NC1	NANTCOKE:1	1100	50	950

Simulated events on the DTS system

Since the existing simulation tools for power systems, like the e-terra simulator, model only the electrical behavior of the underlying transmission infrastructure, mechanical failures are only relevant when their occurrence alter the electrical variables of the system. As was discussed in Chapter 3, when there is a severe mechanical failure, it is highly probable the occurrence of a short circuit and its direct result is the outage of the failed transmission line. The consequent topology change can trigger additional problems in the network such as overloads, voltage drop or angular instability. In the following simulation cases, a generation scenario was established in the EMP60 model to simulate overloads and islanding conditions after the outage of the line Martdale – Ceylon 345 kV.

A case in which the system evolves to a normal state after the outage of the line Martdale – Ceylon 345 kV is shown next. Refer to Figure 19 and Appendix A for a complete description of the EMP60 model. The direct effect of the outage of the line Martdale – Ceylon 345 kV is the overload of the line Chenaux – Picton 345 kV to 711 MVA, as can be seen in the pre and post fault conditions shown in Figure 20 and Figure 21. However, since the transfer limit of the line is 700 MVA, only a minor shift in generation is required for returning to normal transfer conditions. The evolution of the voltages, line flows and frequency are shown in Figure 22 to Figure 24.

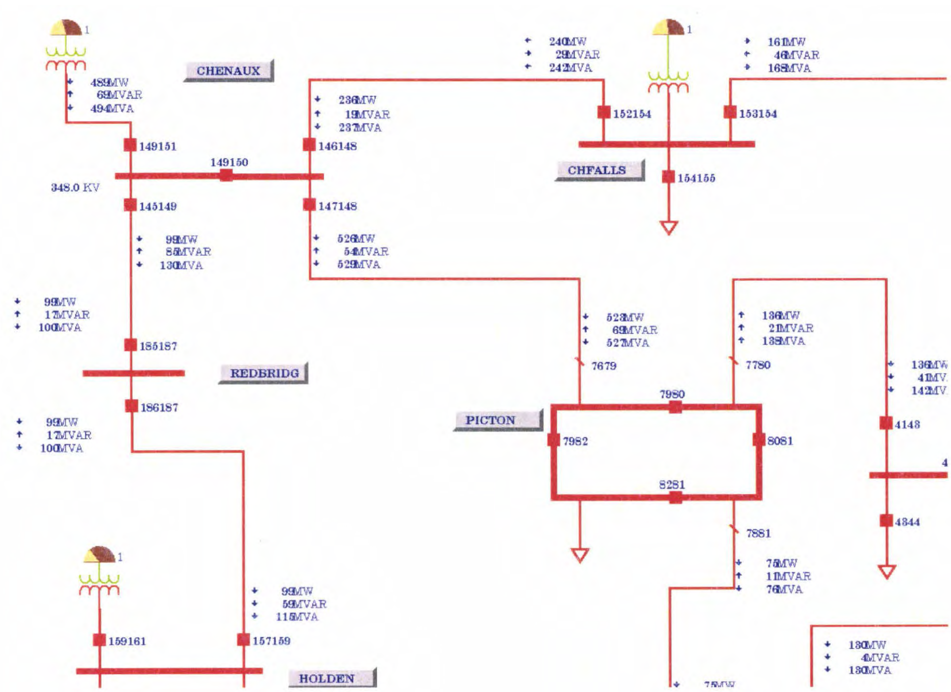


Figure 20. Pre-fault conditions

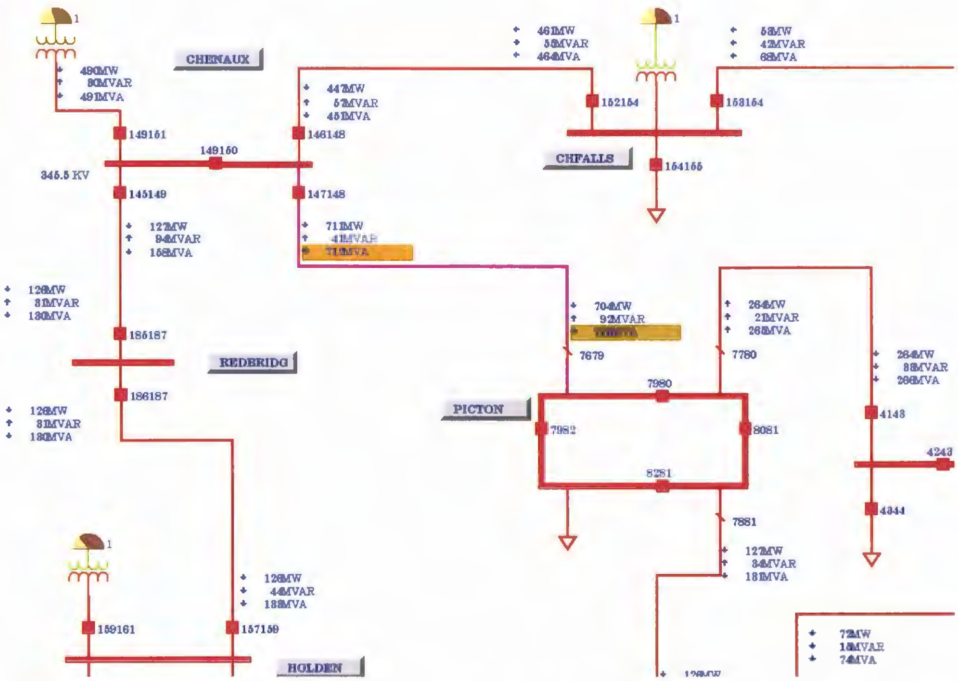


Figure 21. Post-fault conditions after the outage of the line Martdale-Ceylon 345 kV, Chenaux-Picton 345 kV at 101% load

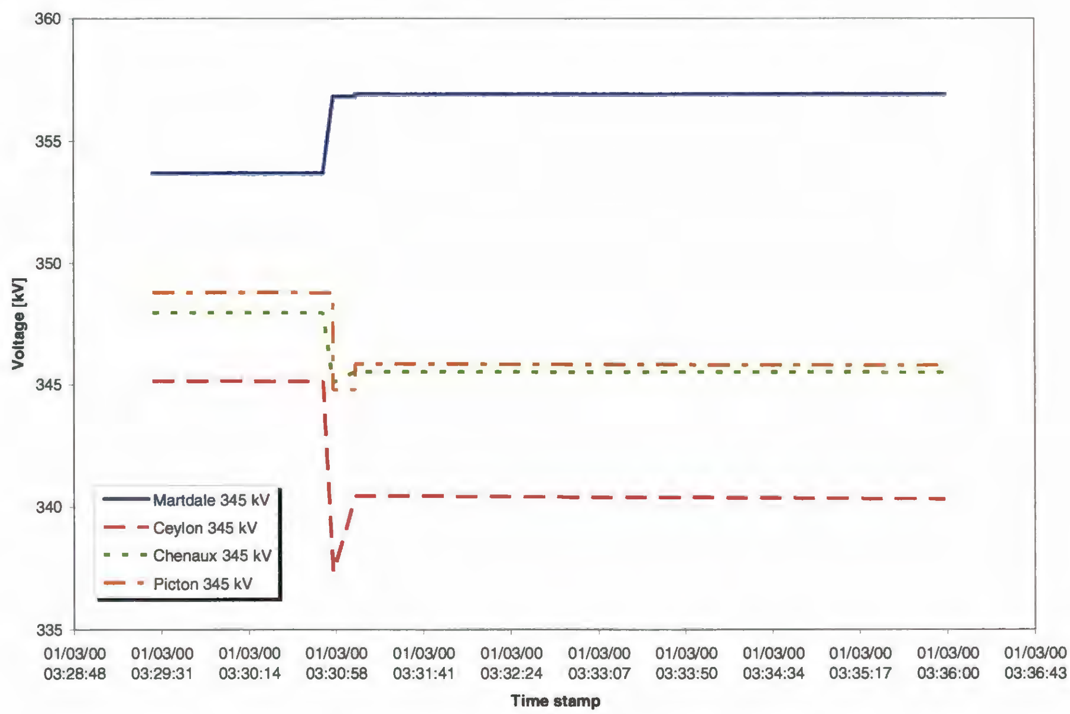


Figure 22. Voltage evolution – Normal case

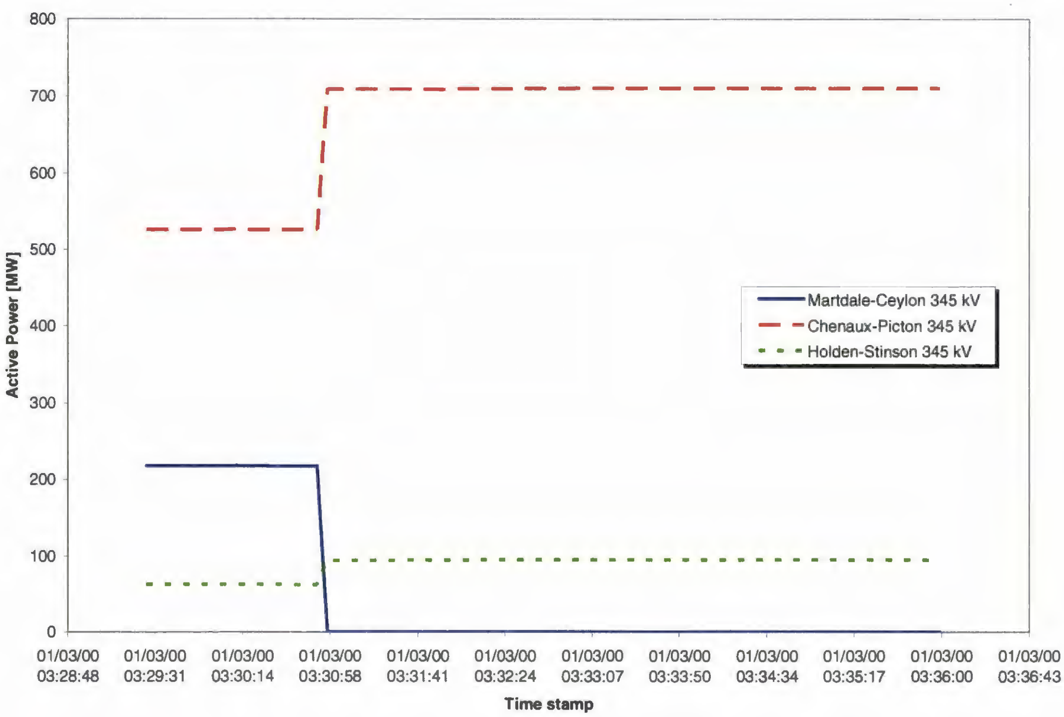


Figure 23. Line Flows – Normal case

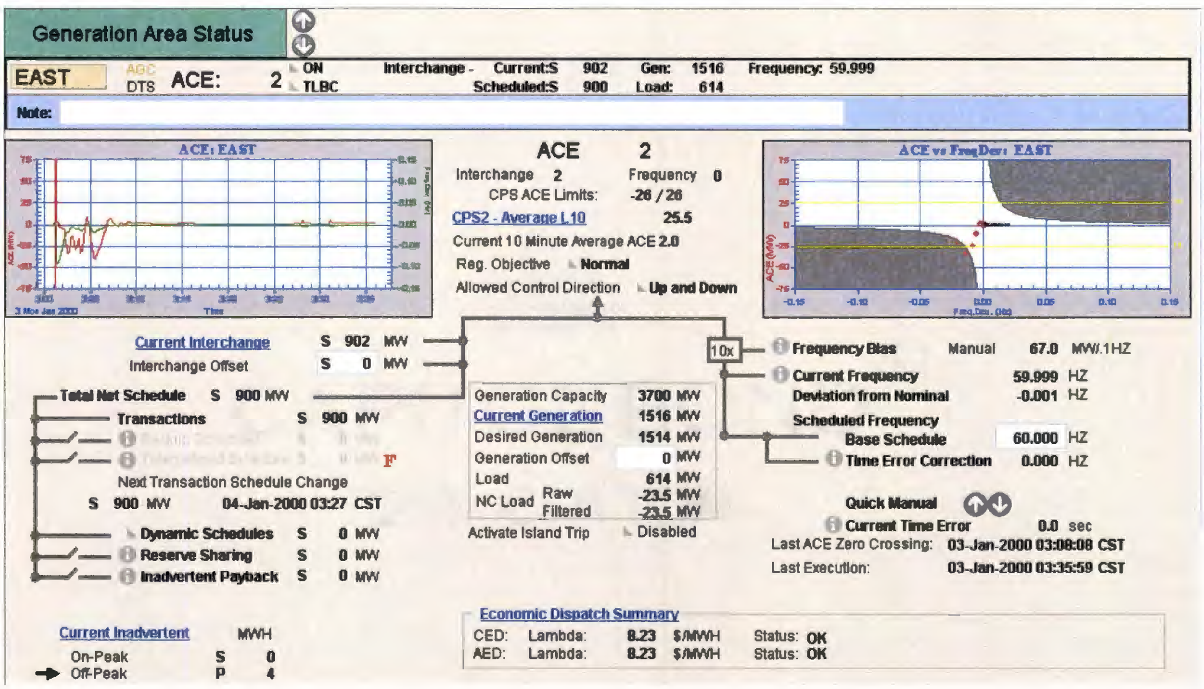


Figure 24. AGC status – Normal case

In the previous case, the interchange between the ECAR and WEST areas was 800 MW. Increasing it to 1000 MW and simulating the outage of the line Martdale – Ceylon 345 kV which could be envisioned as a loss of a line due to mechanical factors, produces the overload of the line Chenaux – Picton 345 kV to 843 MVA (125%), as shown in Figure 25. In this situation, the operating procedures recommend trying to reclose the outaged line, and if it is not possible, the system should be driven to a secure state.

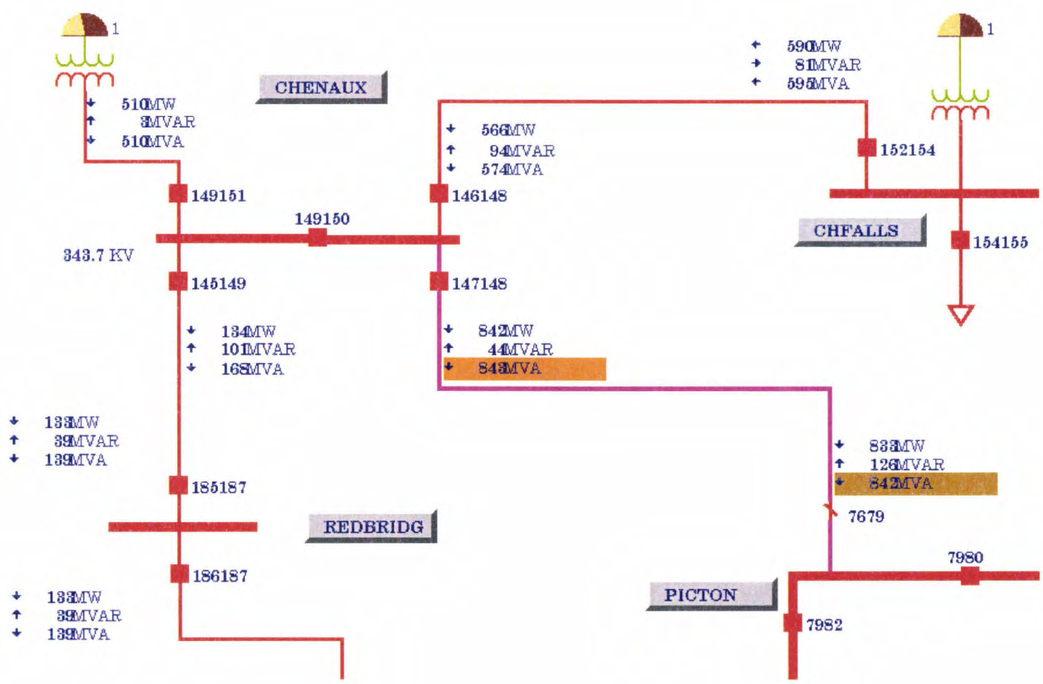


Figure 25. Post fault conditions after the outage of the line Martdale-Ceylon 345 kV, Chenaux-Picton 345 kV at 120% load

However, if in the time spent for reclosing the line an additional outage occurs in Chenaux – Picton 345 kV due to its overloaded condition, the system evolves to the state shown in Figure 26. There could be a variety of causal events for the undesired outage of the overloaded line: Hidden failures, operation of overload relays earlier than expected or excessive sag inducing a short circuit. As will be shown next, this anomaly triggers a cascading event that would produce a collapse in the power system, or its islanding in the worst of the cases. Any action oriented to reduce the power flow in an overloaded line taken at the appropriate time, will help to avoid the consequences of its undesired tripping.

If there are no additional outages, or if the subsequently overloaded lines are not tripped by their protection devices, the power system experiences a voltage collapse as shown in Figure 27-Figure 28. The AREVA DTS simulator indicates a collapse condition by the lack of convergence of the power flow. In this case, the message log of the power system model of the DTS stated that there were generalized low voltage conditions during the time after the outage of Chenaux – Picton 345 kV and before the non-convergent power flow.

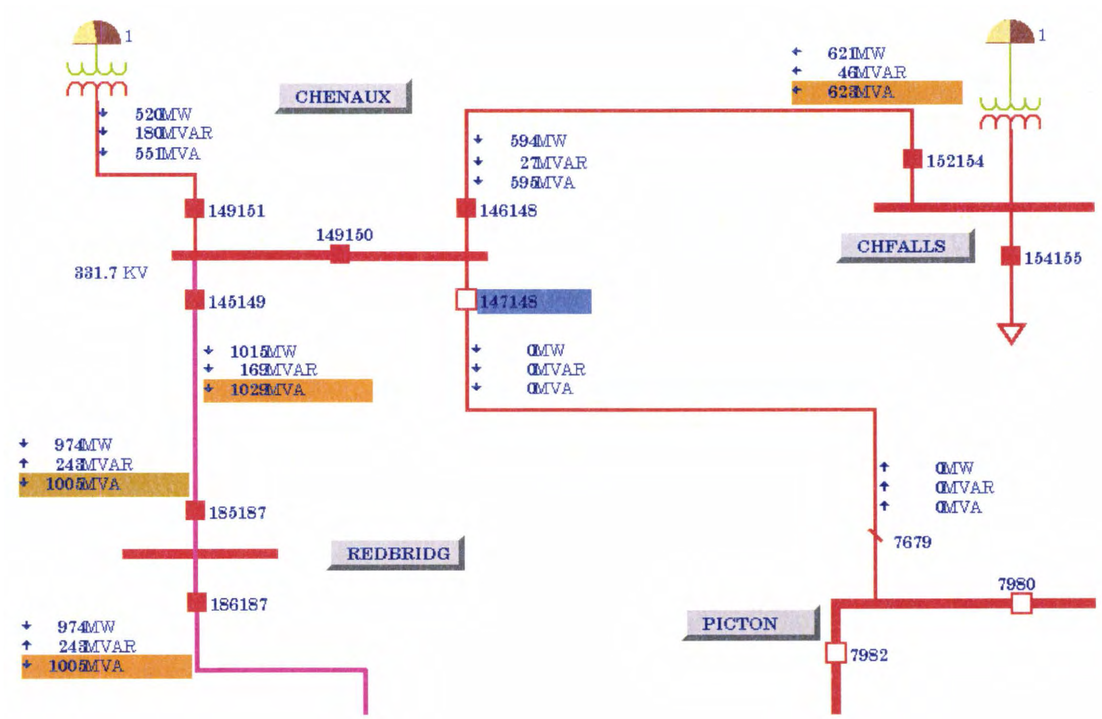


Figure 26. Post fault conditions after the outage of the line Chenaux-Picton 345 kV

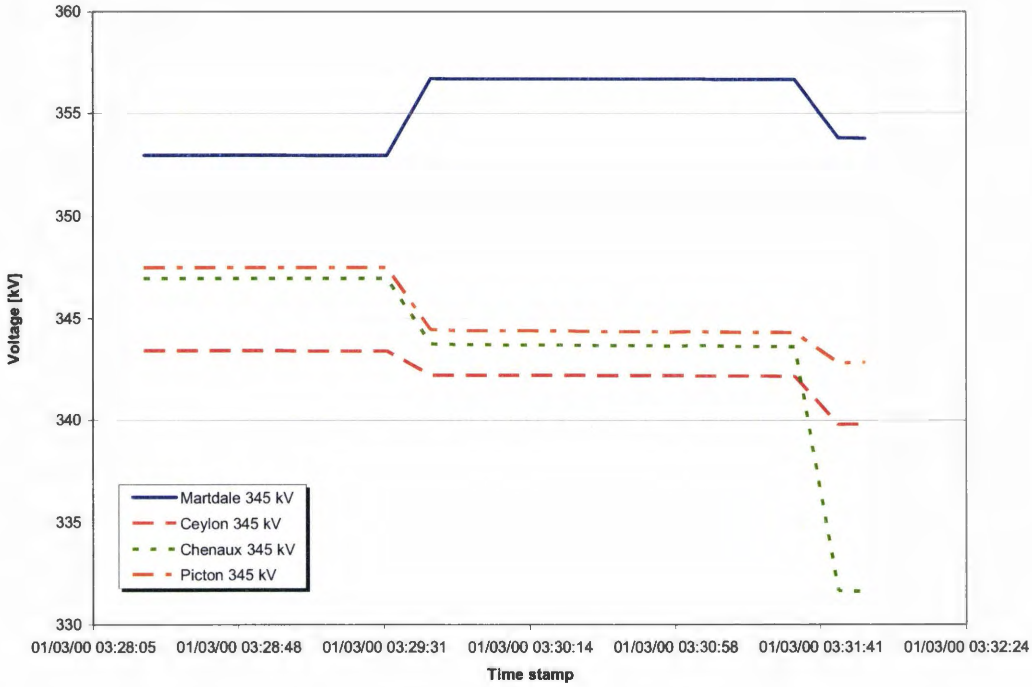


Figure 27. Voltage evolution – Collapse case

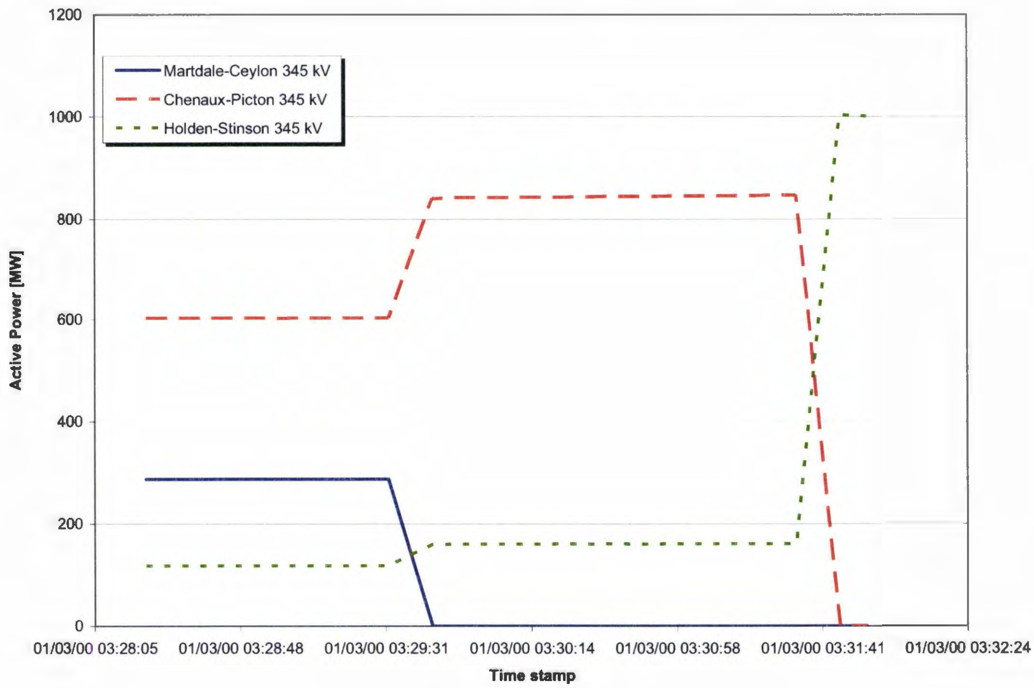


Figure 28. Line flows – Collapse case

If appropriate supplementary protective measures are taken, the system would avoid collapse by islanding the area ECAR after the second outage. In the following simulation, the line Redbridg-Holden 345 kV was instructed to open immediately after the outage of the line Chenaux – Picton 345 kV. Thus, the power system evolves to a state in which there are two isolated areas with unbalanced load and generation as shown in Figure 29 to Figure 33. The area ECAR will have excess generation and frequency over 60 Hz and the EAST and WEST areas will have excess load with frequency drop according to the unbalance presented. There are no under frequency load schemes modeled in the load of the EMP60, therefore, the evolution of the frequency in the EAST and WEST areas reflects only the dynamics of the load control provided by the governors of the generating units. The AGC in those areas is suspended due to the high value of the ACE as shown in Figure 33.

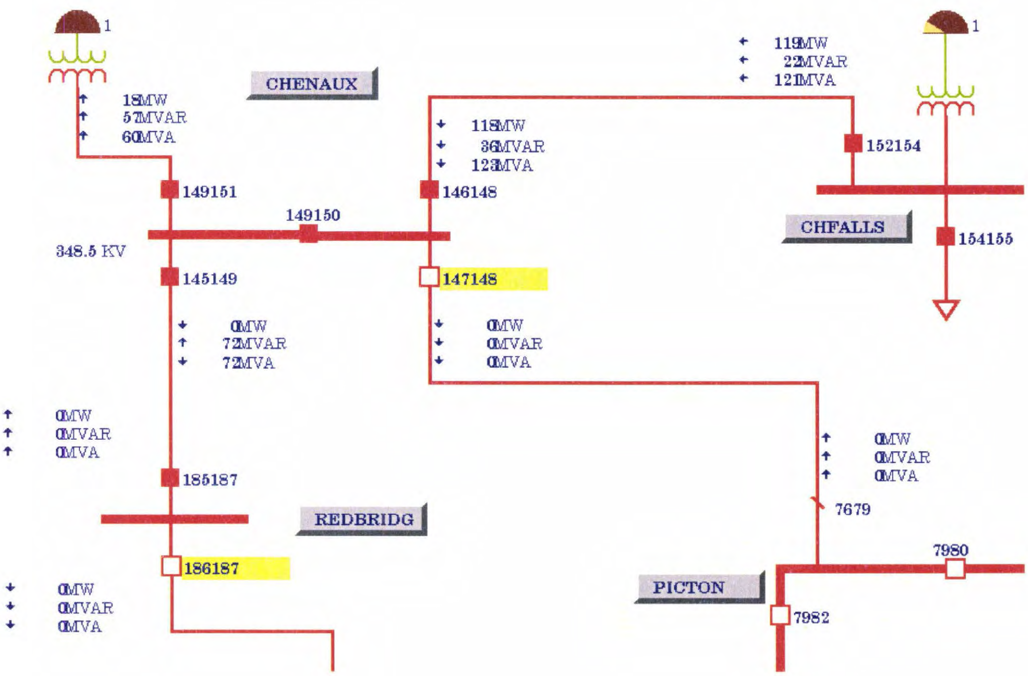


Figure 29. Post fault conditions after the outage of the line Chenaux-Picton 345 kV and Redbridg-Holden 345 kV

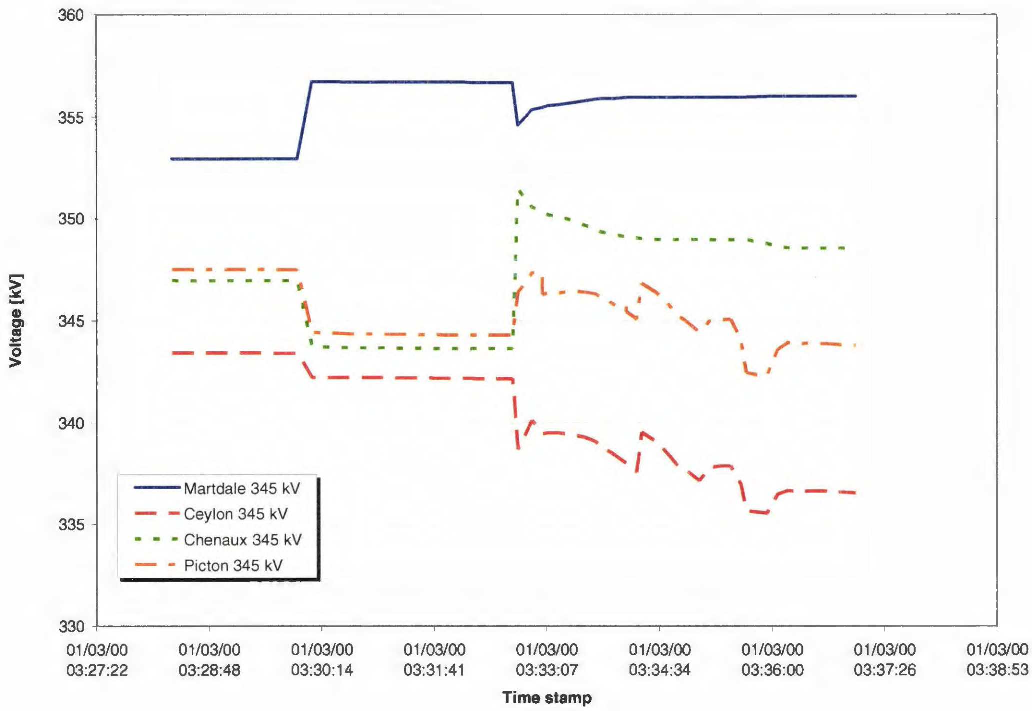


Figure 30. Voltage evolution – Islanding case

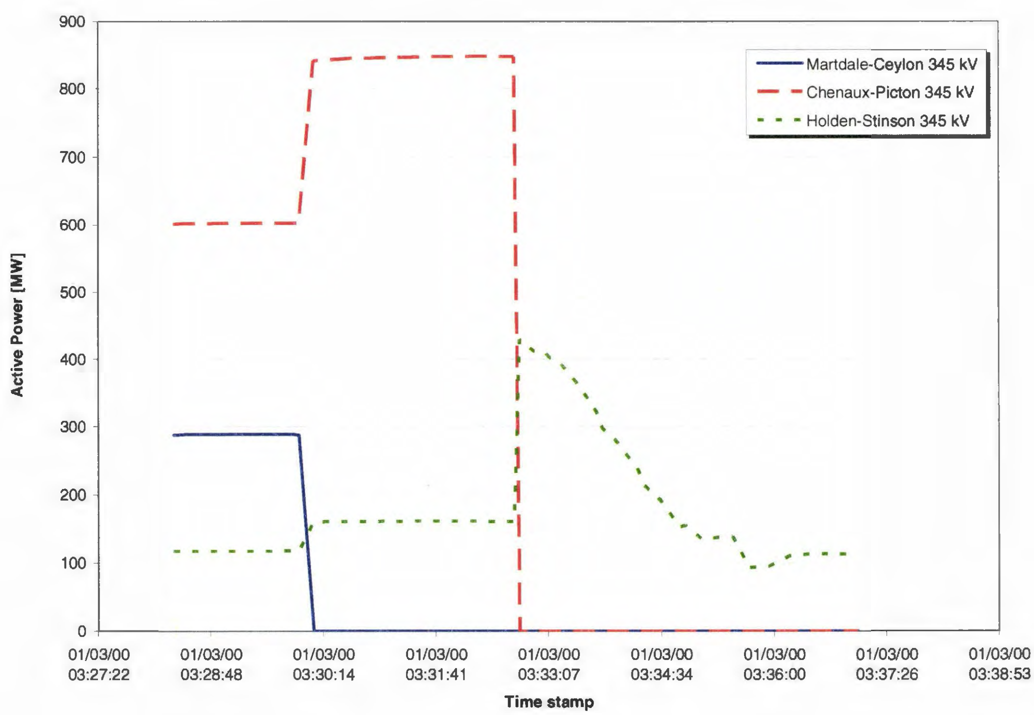


Figure 31. Line flows – Islanding case

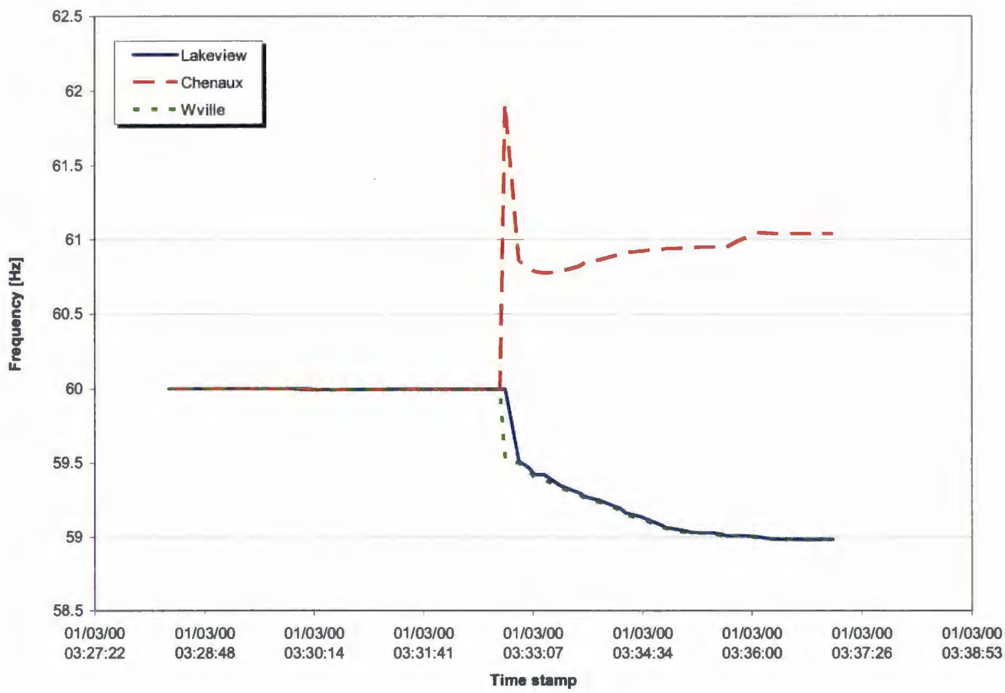


Figure 32. Frequency evolution – Islanding case

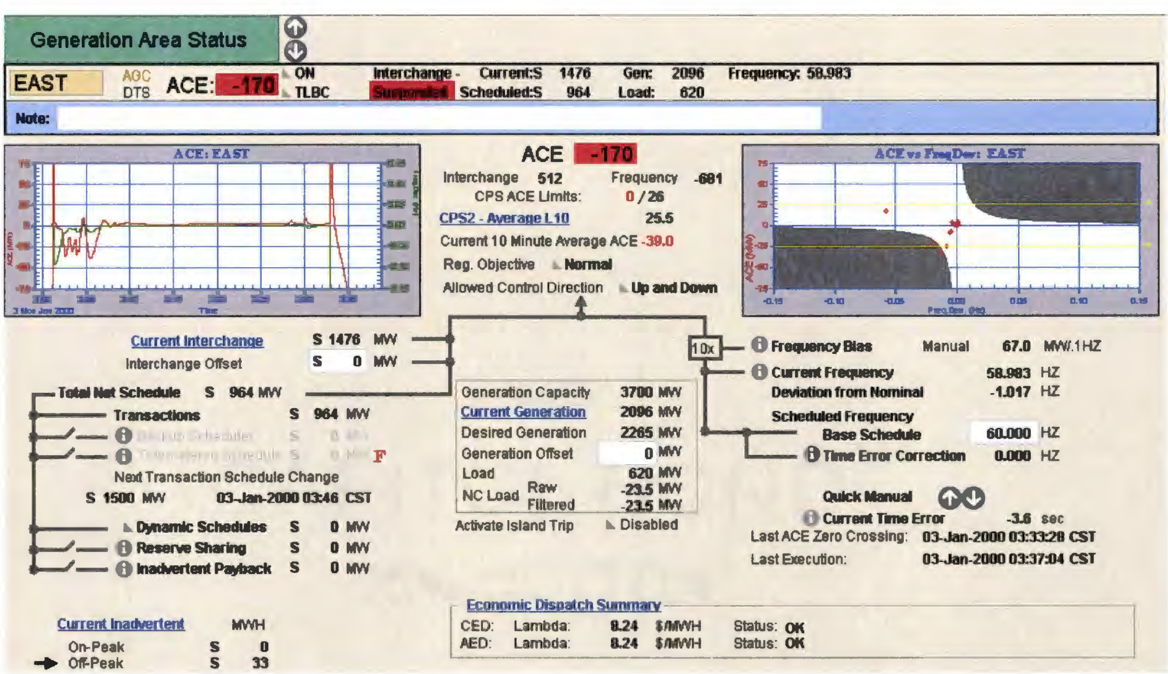


Figure 33. AGC status in area EAST after islanding

CHAPTER 6. PROPOSED TOOL FOR WMSN/EMS INTEGRATION

Mechanical/Electrical system failure modes

The WMSN design proposed in Chapter 4 states that the LSP sends the mechanical health information of its related lines to the central processor with every SCADA cycle. Then, the central processor can analyze the mechanical health data from the two substations at the end of each line and establish a confirmed mechanical heath status for any particular line.

As discussed in Chapter 3, the mechanical health status of a transmission line can be influenced by the environmental conditions and by human actions. Some differences can be drawn between those two influences by means of detecting the spatial and temporal characteristics of the measurements as proposed in that chapter. In the same way, 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. As an example, the tension limits presented in Table 3 can help determine appropriate thresholds for a mechanical health classification algorithm.

This thesis proposes a classification of the mechanical health status of a transmission line based on the severity of the physical conditions as follows:

Normal

In this condition, there is no indication of variables outside the normal operating limits. Tensions in the conductors attached to strain supports are inside the design parameters and are balanced in conductors attached to suspension supports. Vibrations are minimal, all the structures are in vertical position and the temperatures are inside normal operating temperatures, without appreciable differences between close temperature sensors. An integer status value of 0 is assigned to this condition.

Suspicious

In this condition, some of the measured variables stray just outside from the normal range assigned to them. Ice accretion, strong winds or maximum thermal loading can be events associated with this status. As an example, referring to Table 3, tension sensors indicate values below 70% of the established limits for ACSR conductors. There could be indication of vibration in the conductors and supports. Inclinometers and accelerometers in the structures detect small tilt angles. There could also be indications of temperatures in the conductors close to the thermal limits. An integer status value of 1 is assigned to this condition.

Imminent

In this condition, several of the measured variables in the transmission line cross the thresholds established for detecting mechanical problems. However, there is no clear indication of a mechanical failure. Tensions are above 70% of the limit, high vibration levels are detected and structure's tilt angles are measurably apart from the vertical. Temperatures in the conductors are appreciably above the normal thermal limits or there could be indications of hot spots. 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. An integer status value of 2 is assigned to this condition.

Fault

Mechanical failures can be detected by the WMSN in different ways, by the excursion out of limits of some variables, by values near to zero in others or by the complete lack of signal from the sensors. Tension sensors at strain structures can indicate a broken conductor by detecting abnormally high or low values, depending on whether the failure is distant or close to the sensor. In suspension supports, tension sensors can detect abnormally high differences between them or values close two zero in both. Collapsed structures would be detected by tilt angles close to the horizontal. However, when there is a complete loss of signal from any of the sensors or from a LDCP, it is not clear if it corresponds to a failure of the sensor or a mechanical failure in the line. In this case, the dynamics previous to the event and the measurement from neighbor sensors can provide the LSP with sufficient information for classifying it. Additionally, and as discussed in Chapter 3, when a mechanical failure occurs, there is a high probability of the presence of an electrical failure in the system, thus, providing another source for verification. An integer status value of 3 is assigned to this condition.

An xml data file produced by the central processor can supply the mechanical status information to the integration tool in charge of performing the network security analysis. A prototype is shown in Table 9.

Table 9. Prototype of an xml data exchange file for the WMSN status


```
<?xml version='1.0' encoding='ISO-8859-1' ?>
<WMSNStatus>
  <BranchStatus Id='21'>
    <TimeStamp>01/03/2000 03:10:00</TimeStamp>
      <Status>0</Status>
      <WMSNInfo>
        <Tension LDCP='168' Id='TS003' Units='lb'>6000</Tension>
        <Vibration LDCP='169' Id='A001' Units='mg'>340</Vibration>
        <Temperature LDCP='331' Id='T011' Units='F' HS='N'>180</Temperature>
      </WMSNInfo>
    <Dynamics>Wind</Dynamics>
  </BranchStatus>
</WMSNStatus>
```


Electrical faults in the transmission system can be produced by physical events which could be of temporary or permanent nature. In the case of temporary faults, they can be product of lightning, conductor sags, vegetation approach and/or contact. In this case there is a line trip due to relay action, but the physical event producing it is not present when there is intent to put the line in service again. There is no fault indication from the mechanical sensor network, but probably signals of suspicious or imminent mechanical events. Permanent faults, in the other hand, are product of the occurrence of more drastic physical events like downed conductors (1-3), collapsed towers or poles, permanent vegetation contact, etc. In this case, there is a line trip due to relay action and there is a fault indication from the mechanical sensor network.

For each of the different fault types, 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. We are going to focus now to transmission overload management driven by the fault classification. For example: If a line trips and that event produces an overload in another transmission line, the fault classification can provide 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 start immediately the recovering process that can include generation shifting and/or load shedding.

Network sensitivity factors

The real time operation requirement for the proposed tool sets a constraint on the amount of calculations that can be executed for assessing the state of the combined electrical and mechanical subsystems. For this task, linear methods are the most appropriate due to their speed of calculation. However, by using a linear representation of the power system they only provide approximate results of the condition of the system in a determined state.

The DC Power Flow is a simplified version of the decoupled Power Flow problem in which it removes the V–Q equations, and assumes all node voltages equal to the nominal (1.0 pu), thus providing a linear set of equations of the form:

$$\vec{P} = B' \cdot \vec{\theta}$$

Where:

$$B'_{ii} = \sum_{j=1}^{N} \frac{1}{x_{ij}}$$

$$B'_{ij} = -\frac{1}{x_{ij}} \qquad i \neq j$$

The power flows through the branches (Lines and Transformers) of the network are then calculated as:

$$f_l = P_{ij} = \frac{1}{x_{ij}}(\theta_i - \theta_j)$$

A byproduct of the DC power flow formulation is the possibility for obtaining network sensitivity factors. Wood and Wollenberg [48] propose a set of network sensitivity factors using linear relationships that can be drawn between active power injections at the nodes and the active power flows in the branches of the network, based on the formulation of the DC power flow as:

$$\Delta\bar{\theta} = X \cdot \Delta\bar{P}$$

Where:

$$X = [B']^{-1}$$

The *generation shift distribution factor* (*GSDF*) for a branch connecting buses m and n with respect to the injection at node i can be obtained by:

$$a_{li} = \frac{\Delta f_l}{\Delta P_i} = \frac{1}{x_l}(X_{ni} - X_{mi})$$

The resultant generation shift distribution factor represents the change of the power flowing in branch l due to the change in the power injected at node i. It also can be understood as how much of the power injected at a determined node (i) will flow through the branch (l) being evaluated.

In a similar manner, the *line outage distribution factor* (*LODF*) for a branch connecting buses m and n after the outage of the branch k between nodes i and j can be obtained by:

$$d_{l,k} = \frac{\Delta f_l}{f_k^0} = \frac{\frac{x_k}{x_l}(X_{in} - X_{jn} - X_{im} + X_{jm})}{x_k(X_{nn} - X_{mm} - 2X_{nm})}$$

In this case, the line outage distribution factor represents the change of the power flowing in branch l due to the removal of the branch k from the network.

As proposed in [48], superposition can be applied for calculating the effect of changes of the power injections in different nodes and/or outages of lines thanks to the linear nature of the sensitivity factors. A particular calculation used in this thesis combines the GSDF and LODF sensitivity factors for obtaining a modified GSDF for a branch l after the eventual outage of the monitored line k. In this case, the formulation for the new GSDF is:

$$a_{lk,i} = a_{li} + d_{lk} a_{ki}$$

Obtaining recommendations for alleviating line overloads

By using the network sensitivity factors presented in the previous section, and taking advantage of their linear nature, the most contributing power injections to a line flow can be identified by examining the resultant GSDF vector for a particular line. As noted before, the GSDF vector for each line contains the relative contribution of each injection to the flow of the line, taking into account that any change in the power injection is compensated by a change in the opposite direction by the reference node.

For determining the most contributing combination of injection increase and decrease, it is necessary to identify first the node with the maximum value of GSDF in the original GSDF vector as:

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

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

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

Once it is established, the most contributing combination of injections 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 propose to use the previously identified set of four nodes for determining the appropriate changes in their injections for managing the overload in a particular line, having that the generation in neither of those nodes is involved in the AGC function. In such case, 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 changing nodes 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. Using the ramp parameter of the generating unit in a node, the reflected rate of change of the power flow in a line caused by the change in the generation is given by:

$$Ramp_{li} = a_{li} \cdot Ramp_i$$

Then, the contributions of the generating units selected in each direction (up or down set) are combined. The change of flow in the line, relative to the contribution of the ramp of each generation in the set is found by:

$$\Delta f_{li}^{up/down} = \frac{Ramp_{li}^{up/down}}{\sum_j Ramp_{lj}^{up/down}} \Delta f_l$$

From the definition of the generation shift distribution factor, the change in each generation required to alleviate the overload is given by:

$$\Delta P_i^{up/down} = \frac{\Delta f_{li}^{up/down}}{a_{li}}$$

Then, by substitution and simplification:

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

Given the linear nature of the network sensitivity factors, the recommendations calculated by the previous formulation are not exact. The resultant line overload relief in the actual power system could bring the line close to the loading limit, but at a value slightly over or below it. If the calculations are done in an iterative fashion, i.e. every AGC cycle, the inaccuracies inherent to the linear representation can be reduced. Using this approach, the recommended incremental change in generation for each unit at every cycle (with time step T) is given by:

$$\Delta PI_i^{up/down} = \frac{\Delta P_i^{up/down}}{T}$$

Since $Ramp_{li}$ provides the rate of change of the power flow in the line due to the change in generation (up or down) in node i, then, for each direction,

$$\frac{\Delta f_l}{\Delta t} = \sum_i Ramp_{li}$$

represents the rate of change of the power flow in the line due to all the generation changes in one direction (up or down). By selecting the smallest absolute value between the calculations for Up and Down generators, it is possible to obtain the expected *speed of overload relief.* Thus, the time required for overload relief can be calculated as:

$$\Delta t = \min\left(\frac{\Delta f_l^{Up}}{\Delta t}, \frac{\Delta f_l^{Down}}{\Delta t}\right) \cdot \Delta f_l$$

The IPSS software

A Visual C++ program was developed for implementing the generation shift strategy described in the previous section. 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 AREVA e-terra Platform and the mechanical status information from the WMSN.

The interface with the AREVA e-terra platform is built on the DDE service provided by Microsoft Windows, using AREVA's HABDDE server. The interface with the WMSN is provided by an xml exchange file as shown in Table 9.

The IPSS software implements a *power system status* algorithm that executes every 8 seconds, which collects the information from the EMS and WMSN and then calculates the generation shift recommendations. The algorithm's flowchart is presented in Figure 34.

Figure 34. Status processing flowchart

Unfortunately, we were not able to obtain the functionality for inserting the recommendations automatically back into the DTS. Therefore, the recommended generation changes need to be introduced manually through the generation management displays provided by the e-terra Simulator. AREVA is working on the *external data processor* software that would provide that functionality. Once it is available, the status processing algorithm can implement the incremental changing strategy proposed in the previous section, thus, reducing the inaccuracies of the manual approach.

Simulation results

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

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

Extreme mechanical conditions, no overloads

In this simulation, the EMP60 system is operating at medium load. The simulation date and time is January 1, 2000 at 7:50 am. The interchange between areas ECAR and WEST is 650 MW. Figure 35 shows the initial conditions in the vicinity of the Chenaux – Picton 345 kV line.

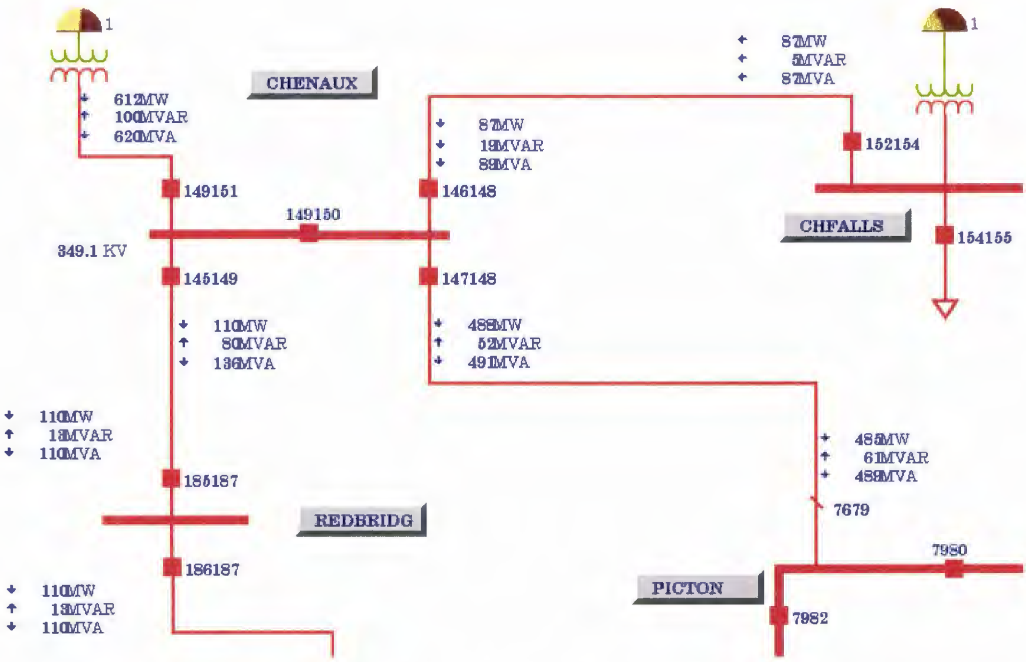


Figure 35. Initial condition at 7:50 am

At this time, the system is in normal conditions, as shown in the IPSS display in Figure 36.

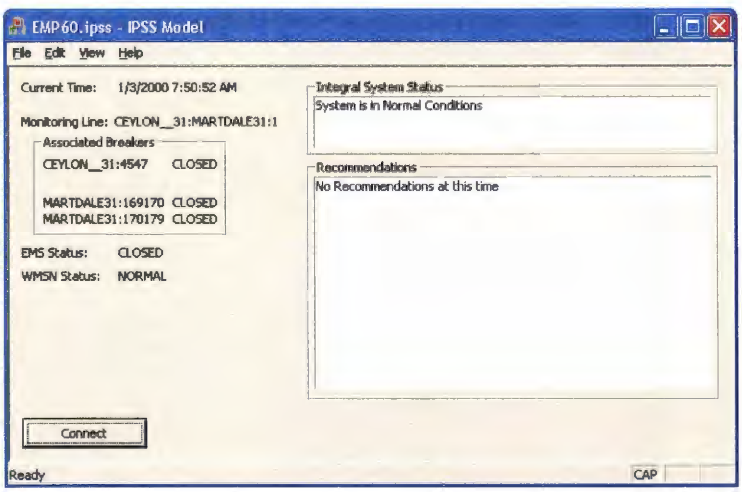


Figure 36. IPSS display for normal conditions

After receiving notification from the WMSN through the xml exchange file, the IPSS indicates the presence of suspicious and later imminent mechanical conditions on the line. However, after processing the electrical status of the transmission system and calculating the network sensitivity factors, the IPSS shows that there are no expected overloads, Figure 37 to Figure 38.

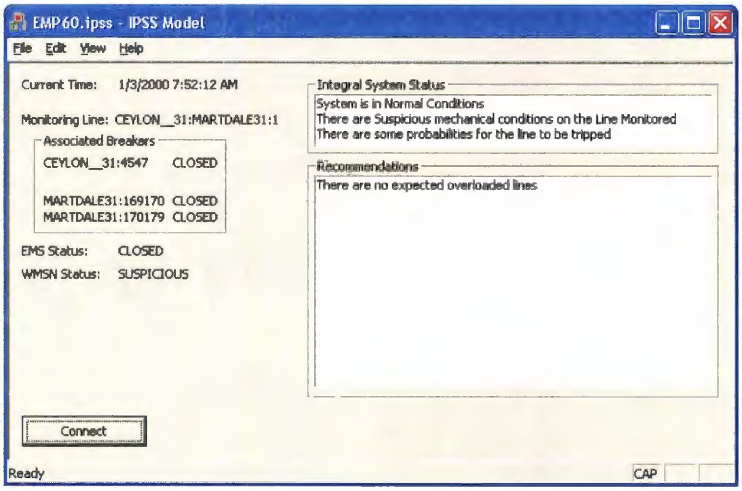


Figure 37. IPSS showing suspicious mechanical conditions, but no overloads

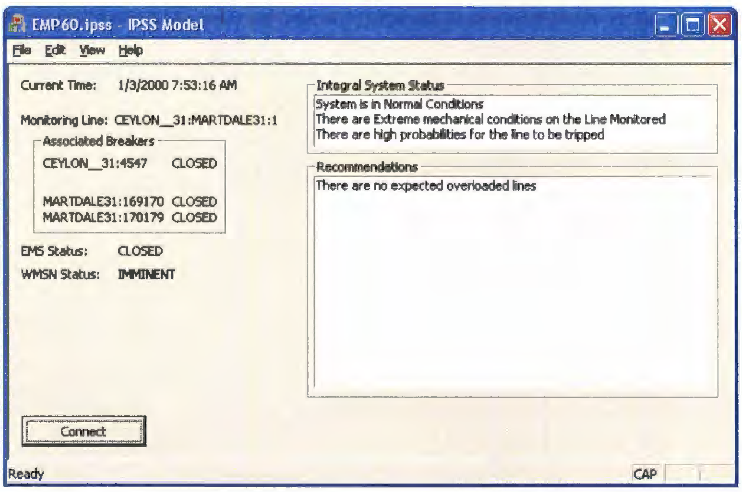


Figure 38. IPSS showing imminent mechanical conditions, but no overloads

After simulating the consequential trip of the line Martdale – Ceylon 345 kV due to extreme mechanical conditions at 7:55:13 am, the system evolves to the condition shown in Figure 39.

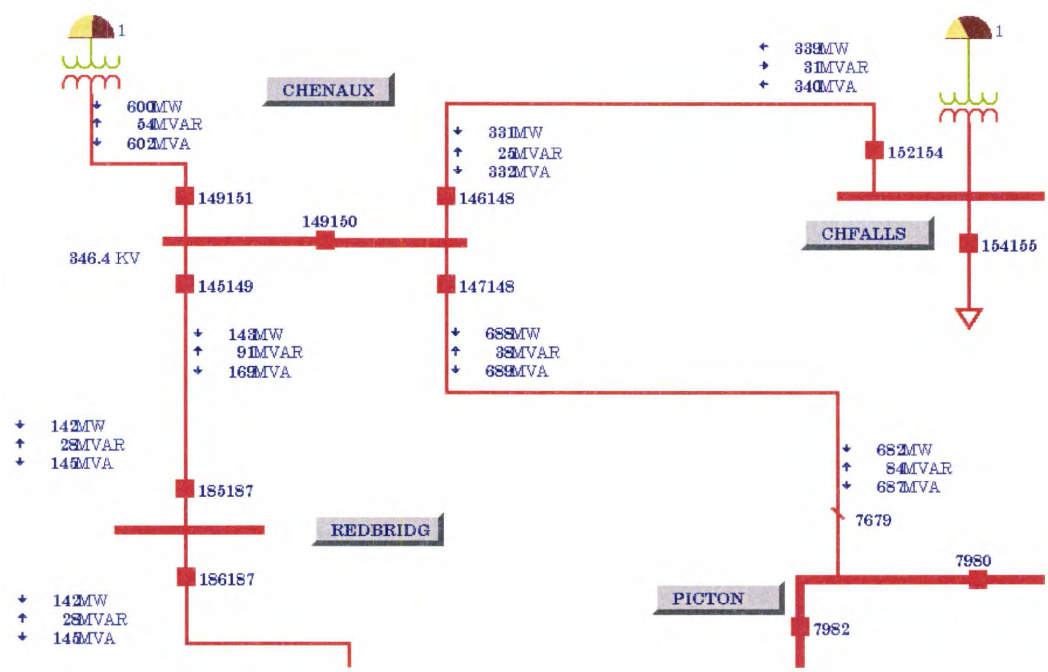


Figure 39. Post fault conditions, no overloads

The IPSS display reflects the new condition of the power system (Figure 40), and Figure 41 presents the evolution of the flow in the tie lines before and after the outage of Martdale – Ceylon 345 kV. As can be seen, Chenaux – Picton 345 kV is slightly below its limit of 700 MVA after the outage, corroborating the calculation of the IPSS status processing algorithm.

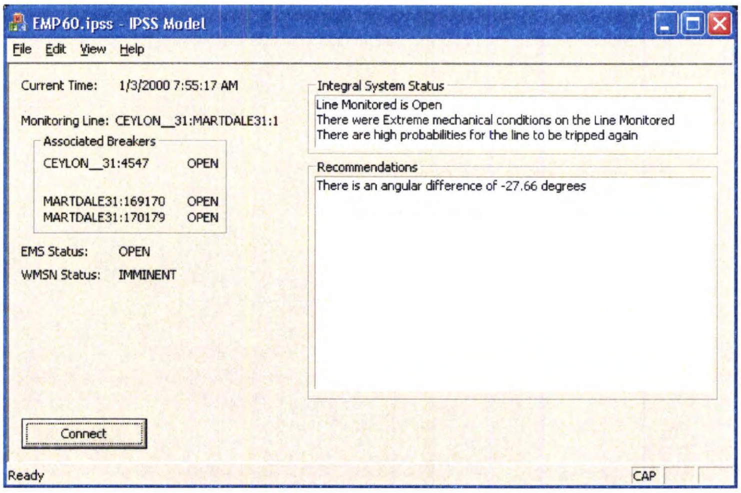


Figure 40. IPSS display after the outage of Martdale - Ceylon 345 kV

Figure 41. Line flows

Extreme mechanical conditions, overloaded elements

For simulating the occurrence of overloads in the DTS, the active power interchange between areas ECAR and WEST is increased to 900 MW. The initial date and time is January 1, 2000 at 7:40 am. The initial condition is of the system is shown in Figure 42.

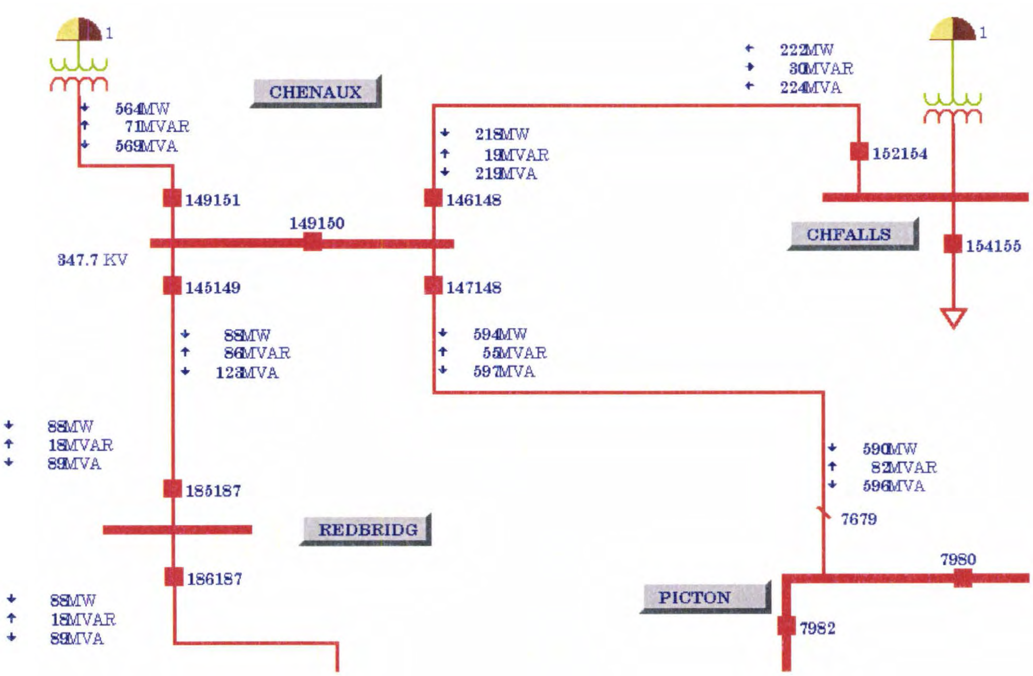


Figure 42. Initial conditions at 7:40 am

Starting from this initial condition, two different evolutions of the power system can be simulated. In the first one, a slow, progressive deterioration of the mechanical condition is simulated, and the operator executes the recommended generation shift actions before the monitored line trips. In the second, a faster evolution of the mechanical condition produces the outage of the monitored line; therefore, the operator takes corrective actions after the line is tripped.

In the first case, the IPSS receives notification from the WMSN, at 7:42:04 am, that there are suspicious mechanical conditions on the monitored line (Martdale –

Ceylon 345 kV), but the line is still in operation. Then, it executes the status processing algorithm, which determines that the line Chenaux – Picton 345 kV can be overloaded if in fact Martdale – Ceylon 345 kV trips, and proposes a set of recommendations. However, for suspicious conditions, it is not advisable to execute the recommendations. They are presented for information only. Figure 43 shows the output of the IPSS for the condition being discussed.

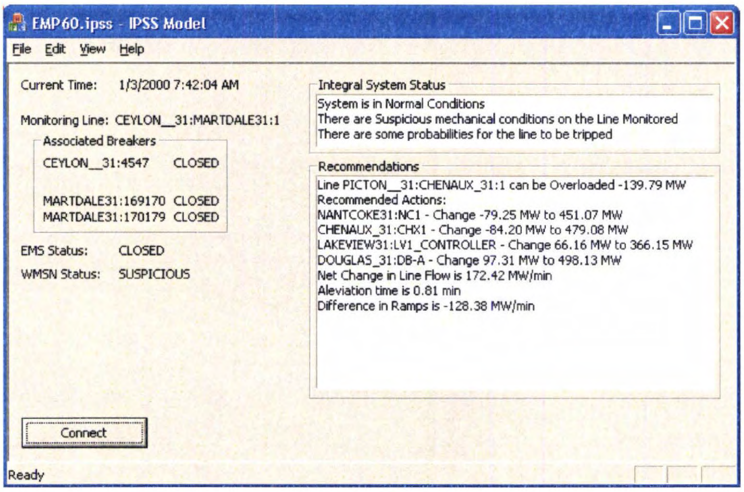


Figure 43. IPSS presenting the recommendations for overload relief

When the mechanical conditions further deteriorate, the IPSS notifies the operator as shown in Figure 44. Since there is the possibility of a permanent fault, the recommendations are implemented starting at 7:45:56 am. The IPSS calculates that the time required for bringing the line to a secure loading condition is 0.82 minutes. Figure 45 to Figure 47 show the evolution of the line flows, generation and frequency for this case.

The outage of Martdale – Ceylon 345 kV due to extreme mechanical conditions is simulated occurring at 7:50:09 am. Figure 45 shows that the final flow on Chenaux – Picton 345 kV is close to its limit of 700 MVA after the execution of the corrective recommendations and the subsequent trip of the monitored line.

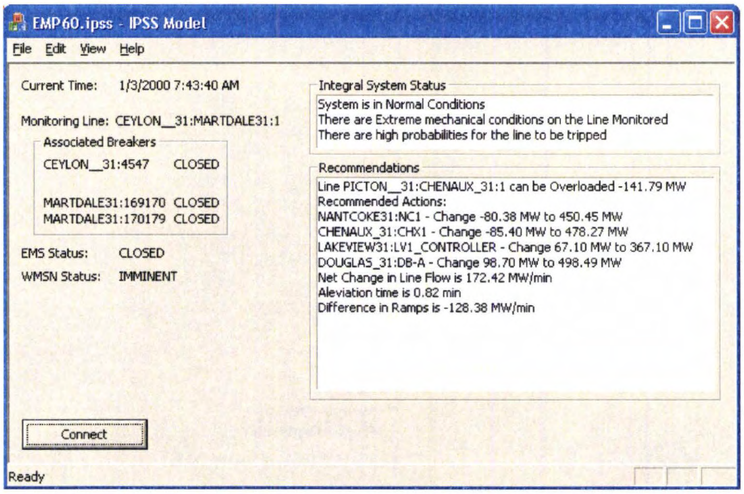


Figure 44. IPSS indicating an imminent mechanical failure

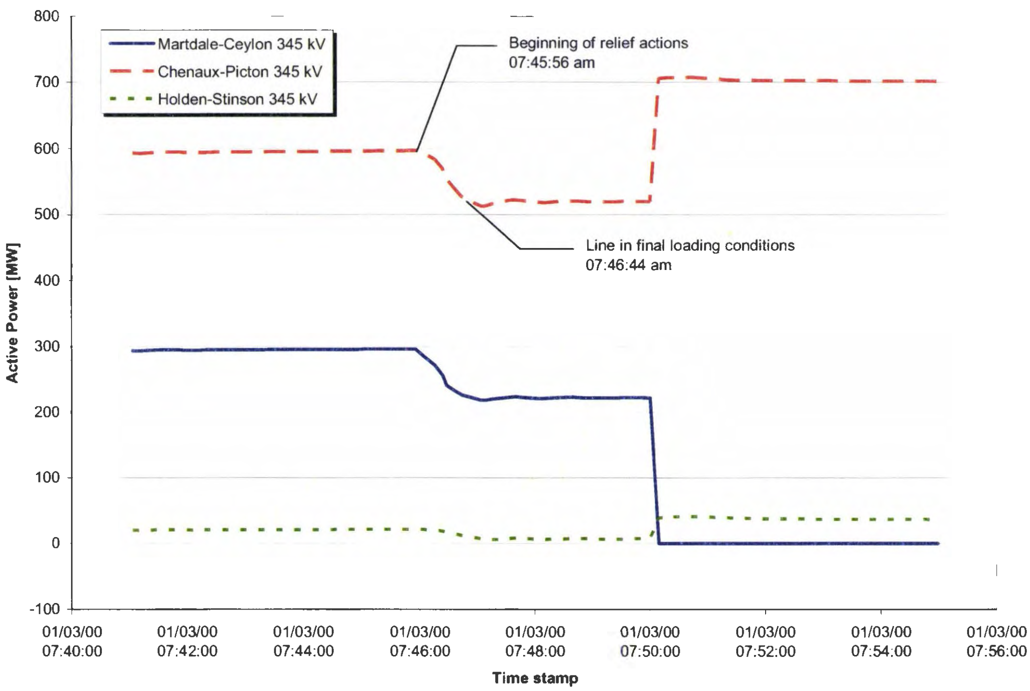


Figure 45. Line flows for relief before the line outage

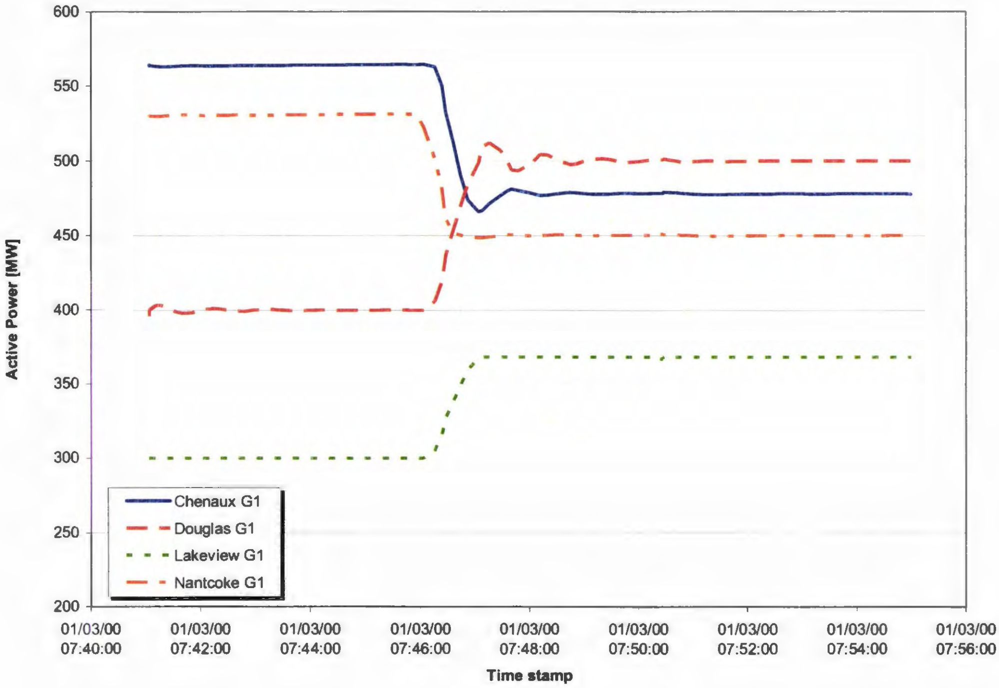


Figure 46. Generation shift

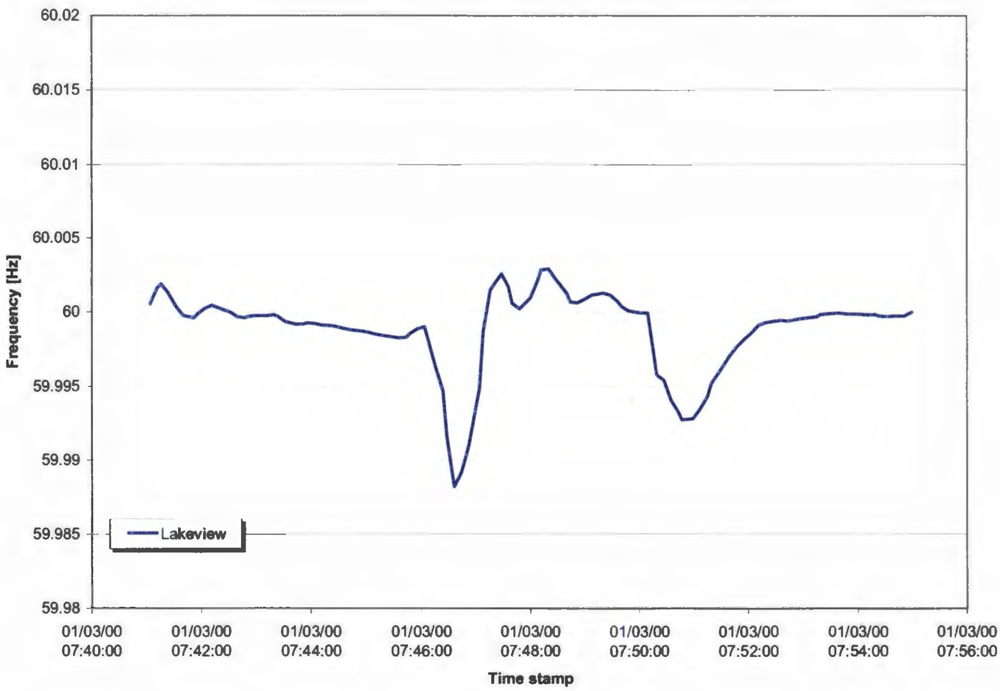


Figure 47. Frequency evolution

The evolution plots of the line flows and the generation show that the time for overload alleviation predicted by the IPSS program (0.82 minutes) is close to the observed in the EMP60 model. Additionally, the IPSS's status processing algorithm detects a difference in the ramps of the recommended units of -128.38 MW/min (Figure 44). The frequency plot corroborates that result by showing an initial frequency drop, indicating that the decreasing units are faster than the increasing units. However, once the changes are finished, the frequency returns to values close to 60 Hz.

When the mechanical conditions produce a sudden trip of the monitored line, the operator in the control center needs to change the operating point to a secure state as quickly as possible in order to avoid possible cascading events. To simulate this case, we start from the same initial conditions shown in Figure 42. The IPSS detects the presence of extreme mechanical conditions leading to a mechanical fault and the simultaneous outage of the line at 7:43:07 am, prompting the operator to take the recommended corrective actions (Figure 48).

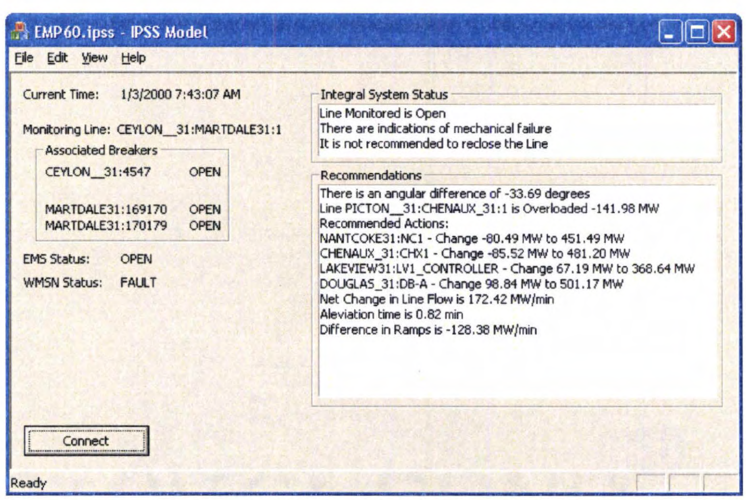


Figure 48

The system condition in the vicinity of Chenaux – Picton 345 kV after the outage of the monitored line is shown in Figure 49.

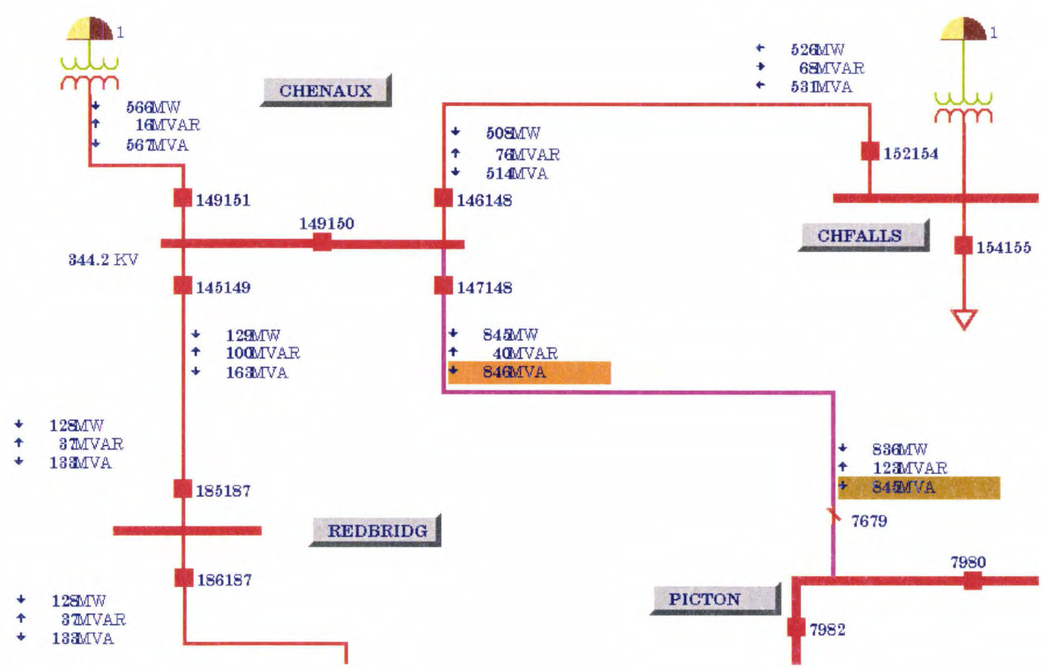


Figure 49. Post fault conditions, Chenaux – Picton 345 kV at 120%

Once the generation shift recommended by the IPSS is implemented, the system achieves a new quasi secure state in the time predicted (0.82 min). However, due to the inaccuracies inherent in the linear methodology, the resultant loading of the line Chenaux – Picton 345 kV is still over the allowed limit. The IPSS display shows the amount of overload and the actions required to take the line to 100% loading (Figure 50). After taking the supplementary recommended actions, the overload of Chenaux – Picton 345 kV is relieved. Figure 51 – Figure 53 show the behavior of the main variables of the power system during the simulation.

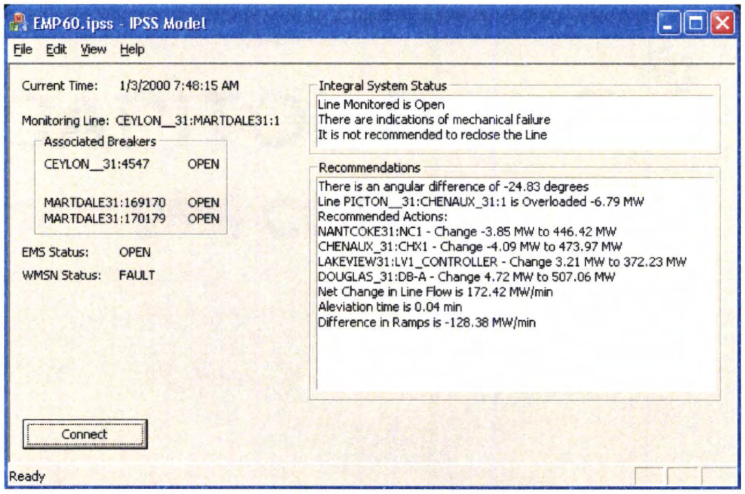


Figure 50

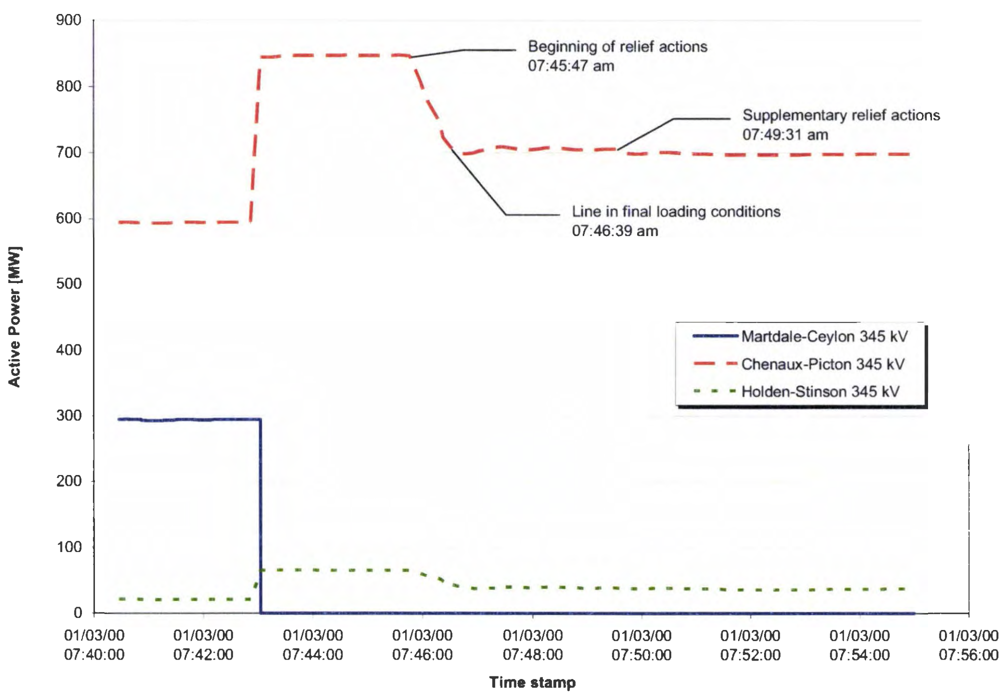


Figure 51. Line flows showing relief actions

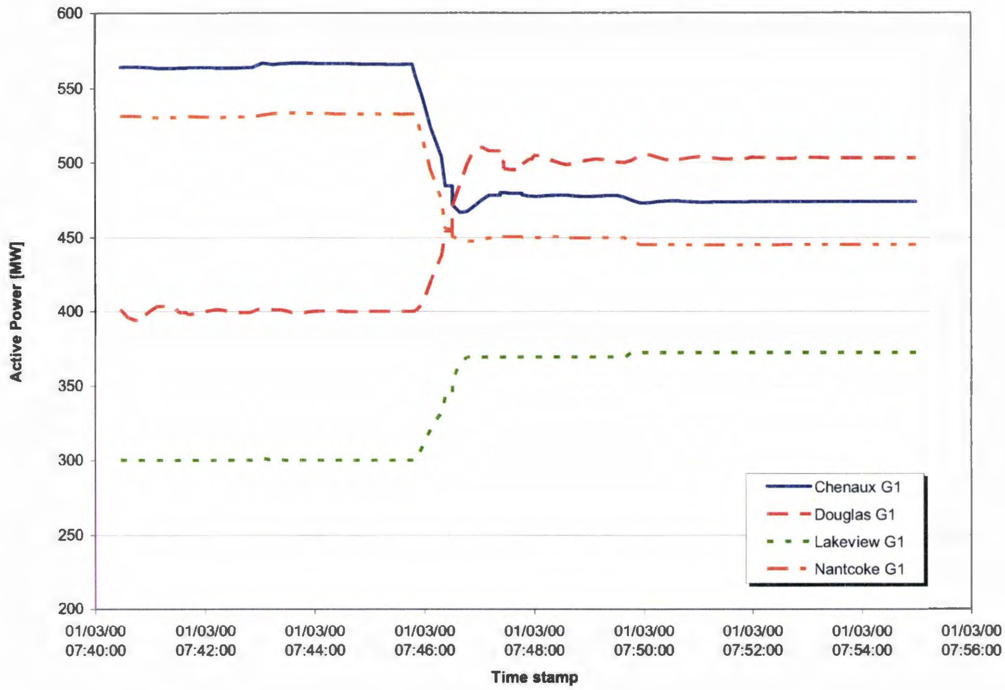


Figure 52. Generation shift

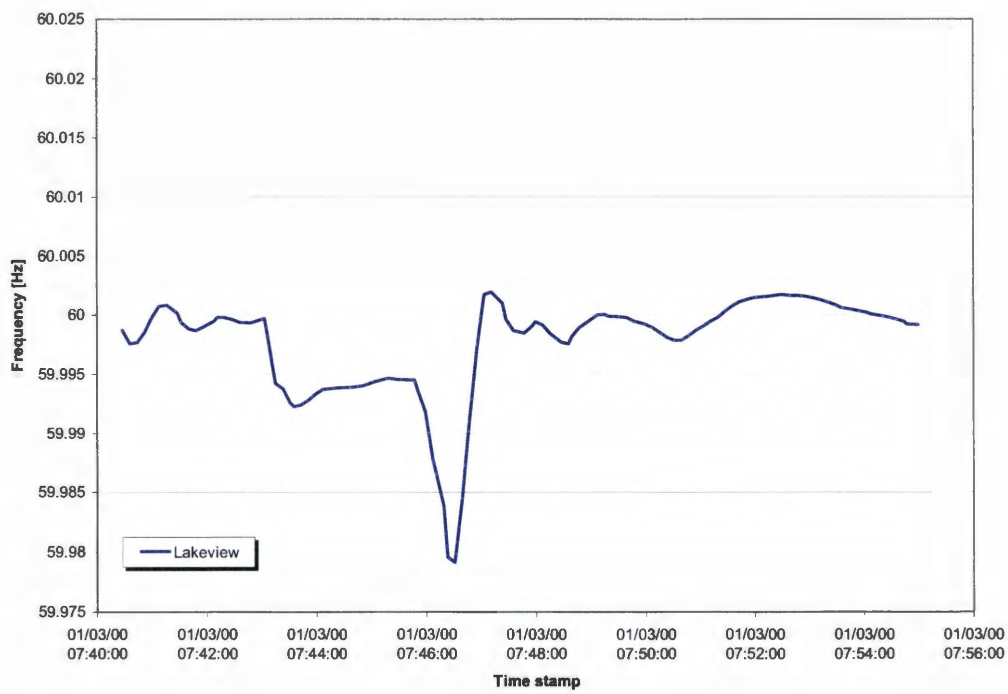


Figure 53. Frequency evolution

The results of the previous simulations demonstrate the benefits of implementing the *wireless mechanical sensor network* (WMSN) along with a power system security analysis application like the IPSS. By providing information about the permanent/temporal nature of a failure, the integration of the WMSN, the EMS system and the IPSS would help operators determine the appropriate actions required to avoid cascading events like those obtained in the simulations in Chapter 5, where there is assumed that no WMSN is installed in the system.

In the first simulation case there is no evidence of overloaded elements after the outage of the line Martdale – Ceylon 345 kV. Even though the WMSN is detecting the presence of potential mechanical problems, the IPSS estimates that the condition would evolve to a reduced risk state, and therefore does not offer recommendations. The first simulations of Chapter 5 and Chapter 6 corroborate this result.

In the collapse and islanding cases of Chapter 5 it was shown that overload of the line Chenaux – Picton 345 kV was the driving factor of the cascading events leading to the final result. The second and third simulations of this chapter show that the use of the WMSN and the IPSS will help reduce the time that the line will be on the overloaded condition. In fact, if an imminent mechanical failure could be detected before an outage of the monitored line (Martdale – Picton 345 kV), the IPSS can command a reduction in the flow of the potentially overloaded line even before Martdale – Picton is opened. The consequence of this is that no overloads would appear in the system after the outage of the monitored line.

In the case of an unexpected trip of a monitored line, which will be the case of a sabotage attack or a rapidly deteriorating environmental condition, the quick identification of a permanent fault gives the operators clear indication of the state of the system. They can proceed immediately to drive the system to a secure condition with the help of the recommendations offered by the IPSS. The benefit now is the reduction of the time in which the overloaded line stays in that condition, thus reducing the risk of an undesired trip.

CHAPTER 7. CONCLUSIONS AND RECOMMENDED FUTURE WORK

Conclusions

This thesis proposes a novel approach for using wireless sensor technology to assess the mechanical health of transmission lines. It is the first known proposed application for wide deployment of smart sensors in transmission lines. The set of smart sensors selected can provide the information required to detect a broad number of environmental and human related events affecting a particular section of a line. During the literature review, it was discovered that there are a number of relations between the measurements which can be exploited for obtaining improved selectivity and classification of the different mechanical events. Additionally, it was found that the dynamics of the mechanical events can also be a source for classifying between environmental occurrences, accidents or sabotage actions.

The ability to apply the finite element theory on a reduced model of the transmission line supports the viability for the implementation of a *mechanical state estimator* for the information collected 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 maintenance, or perform 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. The statistical data and the correlation with confirmed faults can also supply the information for calculating failure probabilities.

The proposed two layers architecture provides a way to overcome the range limitation of the smart sensors installed in the supports, while offering a complete monitoring environment for a transmission line. The separation of the sensing and long distance communication functionalities makes way for the optimization of power management strategies, choosing the most appropriate for each application.

The thresholds for determining the health status of the transmission lines depend on their particular design. Once that information is available, those thresholds can be supplied to the LSP for failure mode classification.

The time response characteristics that can be obtained from the WMSN do not make it viable for fast acting applications like principal or backup protection. However, it is suitable for integration with the data acquisition functionality provided by the SCADA system. The proposed modes of operation enable the collaboration between LDCPs and the LSG in both fast and comprehensive manner. They also support the implementation of failure detection algorithms for the LDCPs.

The proposed algorithm for overload relief is linear, but it was found that it provides good approximations for the final loading of the lines. The fact that it can be executed in real time permits the implementation of automatic overload relief algorithm using a predetermined set of the generating units available.

The simulation results obtained for a system condition in which are expected overloads, show that the recommended actions produce the same results when taken before or after the occurrence of an outage of the monitored line. Likewise, the simulations show that the time predicted by the IPSS for overload relief is a good approximation of the time taken in the actual power system.

The integration of the WMSN and the EMS through the IPSS provides a viable tool for quick assessment of the permanent/temporal nature of a failure, permitting a fast correction of the emergency status of the system. Probably the most evident benefit of installing a WMSN in a transmission line is the ability to provide an early warning system for catastrophic failures when the system is in a highly stressed situation.

Recommended future work

Since this is the first approach to the application of wireless sensor technology to transmission lines, there is still a huge amount of research that needs to be done in order to make this technology practical. Some of our insights about the next steps required to achieve that goal are listed next:

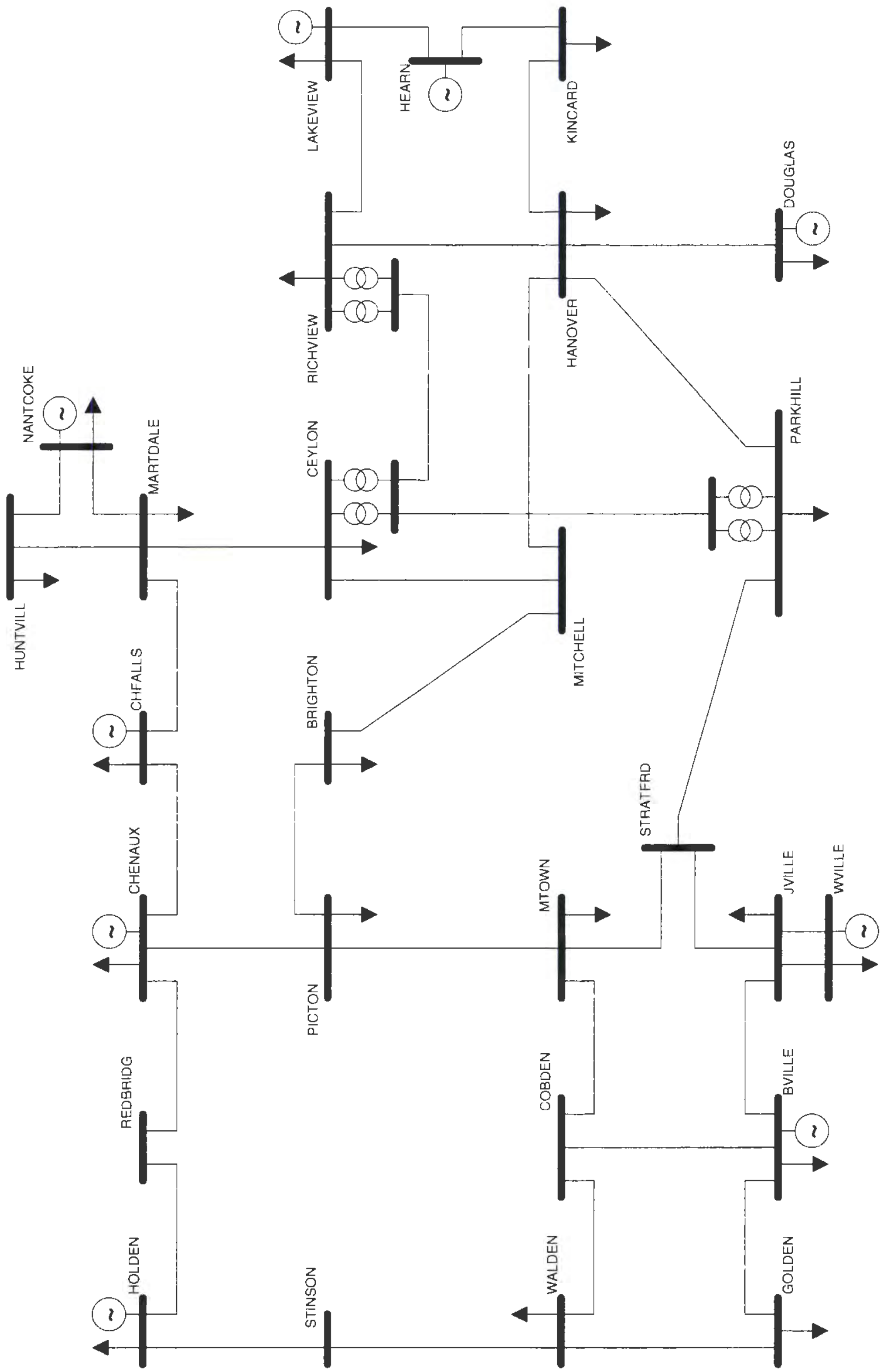
- More analysis needs to be performed for optimizing the placement of sensors in the structures. Involvement of the civil engineering department into the project could be of great help.
- It is necessary to evaluate the effect of the induced magnetic and electrical fields produced by the transmission lines in the integrity of the communications of the WMSN. It is required to analyze the possible interferences due to this effect.
- It is suggested the development of a reduced scale transmission line test bed for research on the relationship between the different variables proposed to be monitored.
- Research on the proposed *Mechanical State Estimator* needs to be accomplished for providing a tool for integration and validation check of the measurements coming from the WMSN.
- It is required to integrate into the analysis the issue of sensor durability given their deployment in potentially harsh environments. The design of appropriate enclosures could guarantee their integrity for extended deployment times without intervention.
- The success of the implementation of the Layer 1 of the WMSN relies in determining the interference levels produced by the proximity to the conductors and in establishing methods to avoid them.
- A more advanced power system security application can be developed for analyzing voltage and islanding scenarios.

- The overload relief algorithm can be applied to more than two units in each direction.
- Insert the recommendations automatically into the EMS. A real time generation control using a set of predetermined generation resources could be implemented just like the AGC function in a EMS.

A number of new applications can take advantage of the implementation of the WMSN in the power system. Below are listed a number of them:

- Dynamic rating of the line by using temperature sensors and strain sensors for measurement of sag.
- Detection of pollution in the insulators by measuring the parasitic currents in the surface of the insulators.
- Take advantage of the communication link between substations for relaying critical information when there is a loss of an RTU.
- Robotic monitoring of overhead transmission lines, using the same mechanical principles than maintenance carts.

APPENDIX. THE EMP60 SYSTEM


LAKEVIEW
HEARN
KINCARD
DOUGLAS
NANTCOKE
RICHVIEW
HANOVER
MARTDALE
CEYLON
PARKHILL
HUNTVILL
CHFALLS
BRIGHTON
MITCHELL
STRATFRD
CHENAUX
MTOWN
JVILLE
WVILLE
PICTON
REDBRIG
COBDEN
BVILLE
HOLDEN
STINSON
WALDEN
GOLDEN

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