Overhead power lines real time monitoring: a future trend ?

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Abstract

This paper gives an overview on the needs which exist to monitor overhead lines as well as on the real time monitoring methods. By real time monitoring not only do we mean to determine the load reserve available on a given overhead line, but also to establish its vibratory analysis.

The ampacity[2] assessment is a key factor to avoid any overload problem: a failure to adequately maintain the clearance distance between an overhead line and the vegetation right below has been identified as a major cause of the August 14, 2003 New York blackout.

The presence of Aeolian vibrations for example is directly linked to the occurrence of the fatigue phenomenon. Therefore is a vibration risks diagnosis important too.

Having examined all monitoring systems available, it arises that an in span autonomous multifunctional and robust micro-systems array is the most attractive future trend.

Résumé

Cet article donne un aperçu des besoins qui existent de surveiller les lignes haute tension en temps réel, ainsi que des différentes méthodes de surveillance disponibles. Par surveillance en temps réel, on entend non seulement la détermination de la réserve de charge disponible, mais aussi l'établissement d'un diagnostic vibratoire de la ligne.

La détermination de l'ampacité[2] est un facteur clé pour éviter tout risque de surcharge : le non respect des distances de sécurité entre une ligne haute tension et la végétation située juste en dessous a été reconnu comme cause principale du blackout de New York (14 août 2003).

La présence de vibrations éoliennes est pour sa part directement liée à l'apparition du phénomène de fatigue. C'est la raison pour laquelle un diagnostic vibratoire est également très important.

Après avoir passé en revue tous les systèmes de surveillance disponibles, il ressort qu'un dispositif à placer sur la ligne, qui soit à la fois robuste et multifonctionnel est la tendance la plus attrayante pour le futur.

Samenvatting

Dit document geeft een overzicht van de behoeften die bestaan om luchtlijnen in real time te controleren evenals van de controle methodes. Met "real time" bedoelen we niet alleen het evalueren van de beschikbare energievoorraad maar ook de trillingsanalyse uit te voeren. De ampaciteits[2]-raming is een zeer belangrijke factor om het even welk overbelastingsprobleem te vermijden: een overtreding van de veiligheidsafstand tussen de bovenleiding en de daaronderliggende vegetatie werd geïdentificeerd als belangrijkste oorzaak van de blackout van New-York op 14 augustus 2003.

De aanwezigheid van trillingen is direct gekoppeld aan het voorkomen van het vermoeidheidsfenomeen. Daarom is ook een diagnose van de trillingen belangrijk.

Na alle beschikbare systemen onderzocht te hebben, doet zich een autonoom multifunctioneel en robuust micro systeem voor als de aantrekkelijkste toekomstige tendens.

Introduction

This document discusses the need for and the methods of real time monitoring (also detailed in [7]) of overhead power transmission lines. It won't be

[1] Ampacimon is a registered trademark and the name of a team of research funded by the «Communauté Française de Belgique», project ARC 03/08-296. The team includes three units of research of the University of Liège. Microsystems: Pr J. Destiné, Ir. J-M. Feiereisen, O. Fontaine Centre Spatial de Liège: Pr C. Jamar, Ir. L. Renson, J-M. Gillis. Transmission and Distribution of Electrical Energy: Pr J.L. Lilien, Ir. S. Guérard, B. Godard. Ampacimon device, system and method have been patented in September 2005.

[2] Ampacity: ampere capacity

limited to maximum allowable thermal limits in terms of ampere capacity (so called "ampacity") reserve available but will also look for vibrations monitoring (any frequencies in the range 0 to 100 Hz) and their effects on ageing, real time thunderstorm effects and corresponding help to load flow redirection in due time, etc…

The real time monitoring informations have manifold returns (non exhaustive list):

– for the national dispatchings, giving access to real time Ampacity level of trunk lines, including interties between countries; to have access to wind storm effect propagation in real time is also a key factor;
- for the utilities using the lines as their business, to be informed in real time on troubles on the network, to detect the lines in which vibrations levels are not sufficiently protected, to be informed about damages, to evaluate permanently the evolution of the fatigue of their lines, to be informed early enough of coming troubles to inform their maintenance staff and/or to redirect the power flow not to loose customers, in other words to safe money;
– for the manufacturers of line cable to better follow actual behaviour of new kind of cables (real time sag, snow or ice overloads, reaction against wind gust, vibration level, behaviour of high temperature-low sag cables, etc…).
– for the scientific world to be informed in real time of many phenomena in order to better dispatch the knowledge about such phenomenon and to learn from it and teach it in a better way.

All these advantages will help to maintain the customers in appropriate service conditions.

In this paper we will investigate the needs for such technologies, the market size, the state of art and future product trend. Some recent results of measurement campaign will be shown.

The needs

Ampacity diagnosis

Ampacity determination is a key factor for all countries (see for example [7, 8, 9], especially for the HV lines (150 kV and over, up to 735 kV). It is a fact that the world OHL length is increasing sensibly every year, noticely due to rapid development of China, India, but also in some regions in Africa. In our regions, the huge market of conductor's replacement on existing line (to increase power flow without increasing mechanical constrains on the tower for example) is clearly a short term good deal.

Still more important is the impact of market liberalisation developed in Europe and USA which will force to have real time information on trunk line. In this context, it can be expected that the dominant trend will be to resort to preventive control to protect the system against the most credible contingencies and to rely on dependable and secure corrective actions to deal with more severe disturbances.

In a deregulated market environment, the priority of market is to maximize their profit. Accordingly, preventive control could be felt as a brake upon business, since it prevents some transactions for taking place, to maintain security margins against hypothetical events. Moreover power systems in European regions as well as north American ones will be operated closer to their limits, since there are increasing difficulties to build new infrastructures while, at the same time, the demand in power keeps growing in most countries.

Under the above described stressed conditions, thermal overloads are pointed out as major threats to system operation. As is well known, these overloads occur when currents exceed the thermal capabilities of the line (this last is in direct connection with actual temperature/sag of the conductor); the isolation of these equipment, by dedicated protective devices or operators, weakens the system, with the associated risk of cascade tripping. The Italian blackout (Sept 28th, 2003) as well as New York blackout (August 14th, 2003) have their origin in air breakdown between trees and power line due to too large sag during overloading.

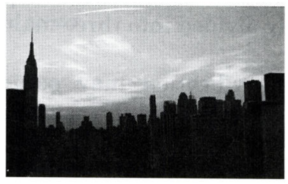

Fig. 0: Black out in New-York, August 14th, 2003.

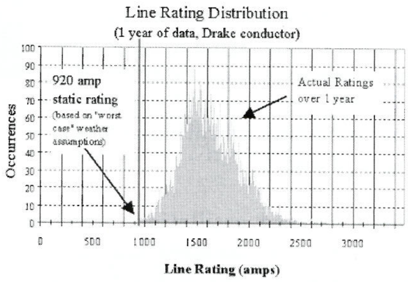

Fig. 1: Example of ampacity real time advantages (courtesy PTI, Dale Douglas)

As stated on Fig.1 the real time ampacity (actual rating) is most of the time much over the static rating which has to be defined in rare conditions so called "worst case weather assumption" (maximum solar heating, maximum external temperature, minimum wind speed, ..). So that a proper way to evaluate in real time the actual ampacity taking into account actual sag on site (which is not only related to weather conditions but also related to the conductor behaviour which may be strongly non linear in high temperature conditions e.g.) would help to better use existing over-head lines up to their actual sag limit.

The dynamic problems to be diagnosed

Overhead transmission lines may be subjected to wind induced conductor motion in the form of Aeolian vibration, conductor galloping and wake induced oscillation. These motions may cause extensive damage to components of the conductor support system or to the conductor itself. Fatigue failure of strands in overhead conductors is the most common form of damage resulting from Aeolian vibration. Aeolian vibration may cause fatigue of other line components such as armour rods, dampers, and insulators.

To receive a high reliability of the transmission line and have a safe electricity network, it is important to have some knowledge about the conductor vibration phenomena and the methods to reduce them.

When a conductor is exposed to wind, several types of vibration phenomena may occur. The vibration types are usually divided into three main groups.

Aeolian vibration may occur on all types of overhead transmission lines when the wind is steady with a velocity between 1 and 7 m/s. The peak to peak amplitude is usually in the range of 0.01 to 1 times the conductor diameter. The proper selection of safe design tension, conductor self-damping, use of dampers and armour rods are basic measures to reduce the effect of Aeolian vibration in lines. Typical damages due to Aeolian vibrations are shown on Fig. 2, 3 and 4.

Wake induced oscillations are limited to lines with bundled conductors. It may occur when the wind velocity is steady between 4 and 18-m/s. The amplitude of the oscillations can be from 0.5 to 80 times the conductor diameter and can lead to conductor clashing. The vibrations can be reduced or eliminated by arranging spacers in a relevant way. The sub-conductor separation, sub-conductor arrangement, sub-span staggering are basic measures to reduce the affect from wake induced oscillation.

Conductor gallop can occur in single or bundle conductors with asymmetrical ice load at high and steady wind velocities between 7 and 18-m/s. Galloping appears very seldom, but is very serious because it may lead to failure in only a few hours. The peak amplitude can be from about 5 to 300 times the conductor diameter. The proper selection of ratio of vertical natural frequency to torsional frequency, sag ratio and support conditions are basic measures to reduce the effect from conductor galloping.

Other phenomena to be detected and evaluated

Many other phenomena can occur in severe conditions:

– the breaking of one/some conductor strands, due to fatigue or lightning, does not lead necessary to conductor failure; even sometimes only inner strands can be destroyed (fretting fatigue). Inspection maintenance staff has to locate these disturbances and to restore the situation, which is difficult and cumbersome by visual inspection (with infra-red camera) and sometimes cannot be done frequently enough to detect the problem at the earlier stage;

– the impact of the gust of wind on long span is very difficult to be quantified in particular environment; the monitoring and the actual cable movement during storm would help so much for health monitoring of such situation;

– ice load may lead to dramatic events. An early detection of ice deposit growth may help preventive action to be taken in due time; (Fig. 5)

– tower stiffness may be severely affected due to stay breakage, broken pieces etc…, this has direct action on span dynamics which may be detected and alarmed.

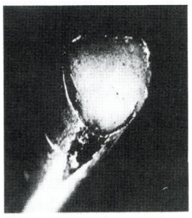

Fig. 2: Fretting and fatigue of second Layer of strands

Fig. 3: Failure surface of fatigued strand

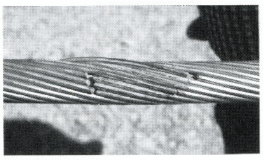

Fig. 4: power line cable strands failures (observation after clamp removal)

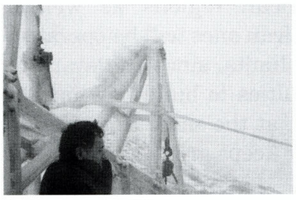

Fig. 5: Typical ice overload problem

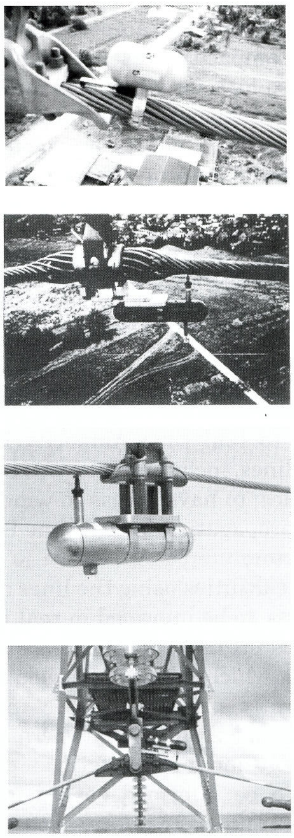

Fig. 6: typical available systems for displacement measurement near clamps to detect «bending amplitude» able to evaluate ageing of cables by vibration occurrences recording.

Available systems

High frequency vibration recorders

Some exist since 1968, most of them are based on displacement measu-rement (so called "bending amplitude") at a given distance (89 mm) from a suspension point (conductor-clamp contact) of the power line (Fig. 6) Numerous cases exist either from Europe, Canada and USA.

The vibration recorder is an aluminium alloy tube. Its weight is approximately 1 kg (including batteries). Vibration bending amplitude (peak to peak) and vibration frequency are measured by displacement transducer (± 1 mm). Frequency is defined as inverse of time lag between two maxima (frequency range: 0.2-200 Hz). Ambient temperature and conductor temperature are

measured by temperature sensors (-40°C to +125°C). Wind velocity perpendicular to the conductor is sometimes also measured with a propeller anemometer (0 to 40m/s). Power supply is a set of 3 Lithium batteries 3.6 Volts (6 months lifetime at default settings). Temperature range: -40°C to +80°C (-30°C to +65°C with wind sensor). More on http://www.roctest.com/modules/AxialRealisation/img_repository/files/documents/PAVICA.pdf
www.sefag.ch

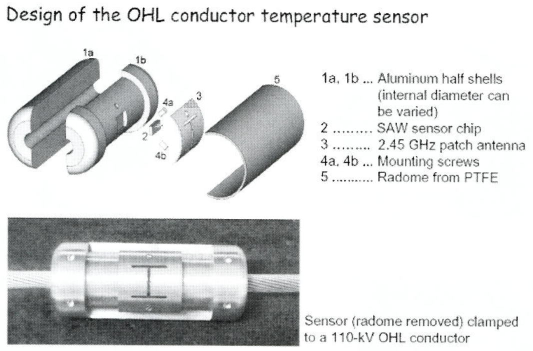

Fig. 7: The SAW temperature measurement (courtesy Pr Hinrichsen, TUD, Darmstadt) http://www.ttn-hessen.de/npkpublish/filestore/77/h_03.pdf

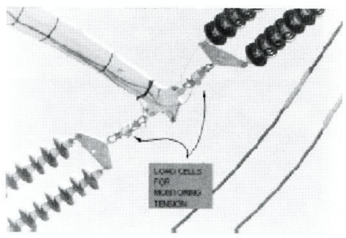

Fig. 8: Typical load cells for tension recording at anchoring level

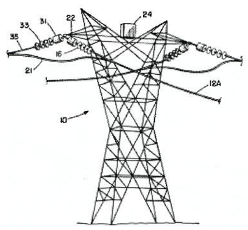

Fig. 9: Tension recording at tower location. Patent 5.235.861 (US) T.O. Seppa, 1993

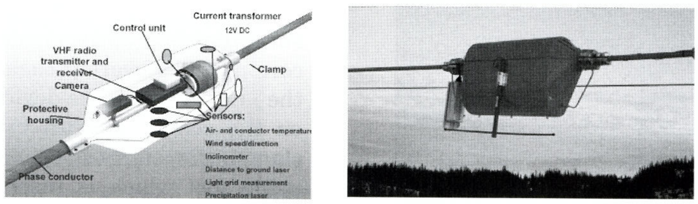

Fig. 10: Multisensor device patented recently (Norway). http://www.protura.no/

Direct conductor thermal temperature measurement

These types of devices are locally installed on the external surface of the conductor.

Example of existing device: the «SAW». Developed by TUD (Darmstadt, Germany) and Siemens (surface acoustic wave) (Fig. 7) this system needs to be installed on a line and afterwards to be targeted by some source of energy from the ground to receive back the temperature information..

Direct measurement of the traction in the conductor

Such measurement needs a load cell in the anchoring system of the line. The system receives its power from local solar cells. The system is commercialised by Valley-cat: http://www.cat-1.com/ (Fig. 8 and 9) and detailed in ref 10.

Multisensor devices

Patent number WO 2004/0388091 A2, (Fig. 10)

This device is able to measure ambient temperature (probe directed outward into the air), conductor temperature, line slope or line sag increase, galloping, wind velocity and direction, concentration of precipitation particles in the air, distance to ground level, quality of line current, and a visual image of the line. Increase in line sag is measured by detecting a slope angle (mercury switches). Snow/ice load can be determined by sag increase measurement and temperature measurement. Wind direction and velocity are measured by traditional wind gauge. The distance to ground level is measured by laser. It is important that the multisensor does not twist around the line. The concentration of raindrops or snow particles in the air can be measured by a particle laser counter. A transformer is used to collect power from the current of the line. There is also a measurement transformer for checking the stability and the quality of the line current. One or several slope gauge (Mercury switch) is used for detecting change in sag. An operator may check visually the situation (power line and its surroundings) with camera fixed on the multisensor. The measurement of the distance to ground level is double-checked by this camera surveillance. Some vibrations sensors are optional. All measured parameters are transmitted by radio to an operation central.

The system patented by M.W. Davis [1] in 1994 is able to measure cable temperature, solar heating, wind speed, electrical current flow. US patent 5.341.088.

Patent number: 5 341 088 (USA), Davis M.W. (Fig. 11)

The sensor-transmitter senses ambient temperature, conductor temperature (where the conductor is clamped), line current, solar radiation, wind velocity and direction, and magnitude of sag (inclinometer). All these parameters are used to define the thermal state of the conductor (vibrations are not measured). Two constant temperature hot wire anemometer are oriented in a « x » pattern. So wind velocity and direction may be determined. The corona reducing antenna sphere is divided into two halves which are spaced to form an horizontal opening. It is important that this air space is not too small nor too large. The electrical components are driven by a power supply which derives power from the transmission line. Two identical «j» shaped magnetic core are

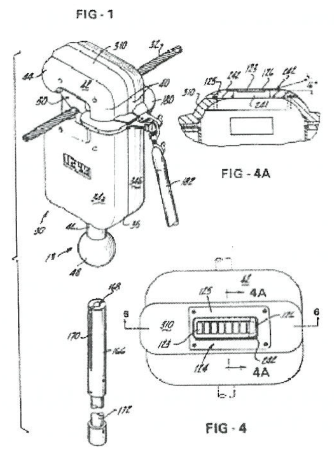

Fig. 11: one of the first in-span temperature sensor

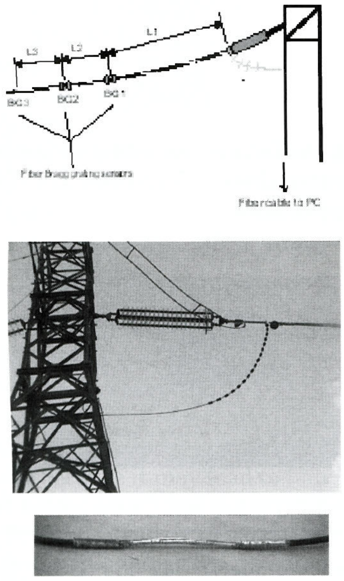

Fig. 12: Fibre Bragg grating for in span real time measurement of vibrations. (Courtesy B. Leif, SINTEF, patent NO 310125)

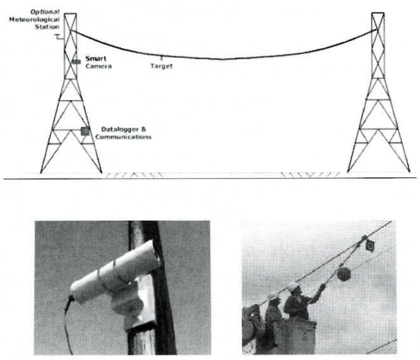

Fig. 13: optical measurement of sag with a camera and a target

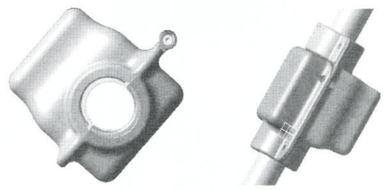

Fig. 14: Artistic views of Ampacimon (with conductor on right hand side)

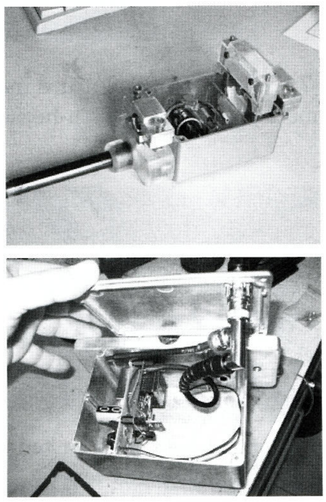

Fig. 15: embedded microsystems

such that the opposing extremities of core portions overlap each other when the jaw is closed. The device is clamped on the conductor with two jaws. The clamping system is opened or closed using tool which is inserted into the antenna tube. The centre of gravity of the device lies below the conductor, thereby providing damping action. Informations are transmitted to a receiving station by radio.

Patent number: NO 310125, B.Leif, SINTEF, Norway. (Fig. 12)

This system uses up-to-date techniques of fibre glass using Bragg gratings (see also ref 11, 12 and 13). Such system is able to measure real time movement of the line (like ice shedding, Aeolian vibration) as explained in former Cable dynamics conferences (see references). The fibre has to be connected to the ground at the end of the span.

Indirect measurement

– Direct sag measurement on one span by optical measurement (Fig. 13) .

Future trend: in span autonomous multifunctional robust micro-systems ?

The system

It seems that roughly thirty years after Murray et al [1 to 6] the idea developed is making a come back not limited to ampacity and using up-to-date electronics microsystems. Internet development is certainly in relation with the come back of such ideas as information may be easily dispatched at any place in the world using the Net. Moreover liberalisation of electricity markets as well as time devoted to maintenance going down are becoming key factors to force the use of such systems.

Ampacimon (example of prototypes on Fig 14 to 17) is a small box (roughly 20 cm long, with section about 15x15 cm), inside which microelectronics has been inserted.

At a specific location an antenna (433 MHz) , with anti-corona design, is installed. Appropriate electric field simulation (3-D) help to design such system, it obviously includes the appropriate radius of curvature of all the box corners and summits.

The fixation to the cable is adapted to conductor diameter (but this is done with only one single box for all cases, the hole for conductor is just manufactured at the end) and is located at the outer parts of Ampacimon. One side (side A) is conductor linked, one side (side B) is conductor isolated. The fixation is done similarly as the one used for air craft warning markers. Before placing Ampacimon, armour rods may be installed on the conductor depending on power lines owners.

The Ampacimon box is in fact divided in two parts (not symmetric) which are assembled together by appropriate fixations. The two parts have flexible links or hinges between them.

The antenna may be protected by additional dielectric "clothes".

Thickness of the box is particularly optimized to minimize the weight of the whole assembly but respecting appropriate rigidity.

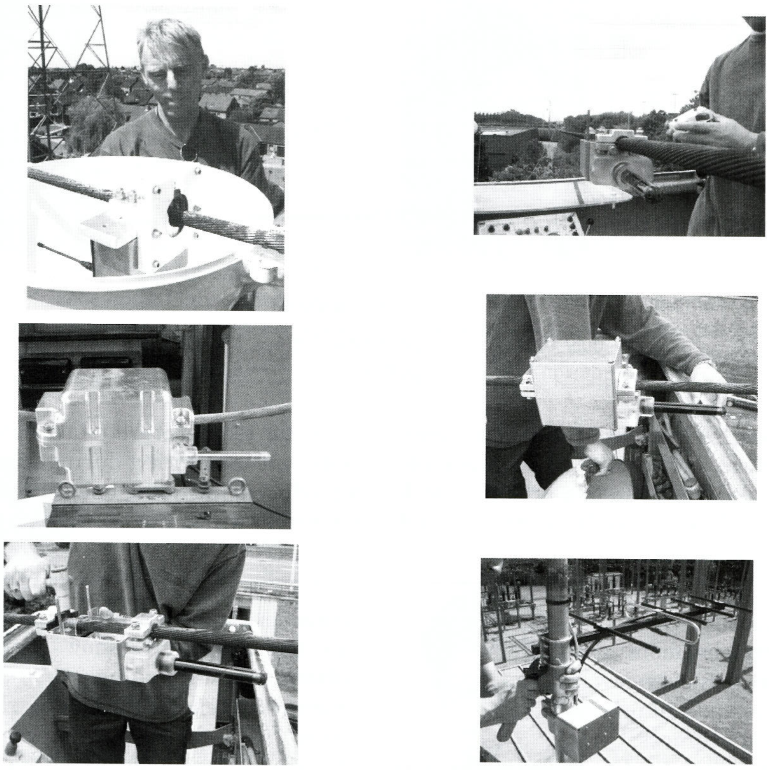

Fig. 16 : examples of prototype installation of Ampacimon HV lines

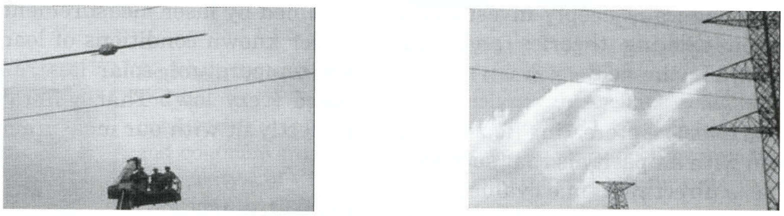

Fig. 17: recent installation (Sept. 2005) of Ampacimon on 220 kV ELIA network in Belgium

The material used for the box may be either aluminium alloy or polymeric material (with appropriate compound and/or extra lattice structure for Faraday cage effect.).

Faraday protection is obtained at two levels: the outer box, anti-corona designed and inner nest box to protect electronics against conductor radiations.

Internal part of Ampacimon contains in appropriate locations:

– a current transformer specially designed for Ampacimon application; the core is divided in two parts reassembled when the two Ampacimon parts of the boxes are fixed together; caution is taken to limit at its minimum the inter core gap; the current transformer design is based on classic transformer theory but we use saturation; the core section depends on load statistics on the line so that we have defined three different cores to cover all cases from 70 kV to 765 kV applications; a special design is used to protect the wiring from overvoltages and the half core placed on one of the Ampacimon parts is potted with a material coming from space industry (hydrophobic , temperature and ozone resistant); the power level of our system is less than 10 Watts and may even go down to less than 10 mW;
– appropriate connectors to link antenna to Microsystem electronic cards; the general "grounding" reference is located at the antenna penetration and is common to transformer and microelectronics;
– optional batteries/ultracapacitors may be added to Ampacimon in the upper part of the box; such energy storage, which has to be managed in their charge level by a BMS (battery management system), may cover cases when line is underloaded or temporarily with no voltage;
– the microelectronics system is equipped with three dimensional accelerometers (Microsystems) and some other sensors if needed; it has some embedded software able to digest measurement and send appropriate information to the antenna;
– the radio system is typically 433 MHz with limited power emission (depending on local standards, 10 mW in Belgium f.e.) able to transmit license free , at about 100 m to a few km depending on system used and terrain configuration; the quality of transmission is also a factor in relation with that distance; caution should be taken not to disturb other local system (like car electronic keys);
– all material is carefully chosen to be able to work in harsh environment with temperature range (basic Ampacimon -20°C to 75°C, advanced Ampacimon -45°C to 150°C). High temperature may be reached owing to military standard components, close to spatial standards;
– ampacimon needs a base station able to receive information (owing to Yagi antenna e.g.) sent by Ampacimon and to transfer them (directly or indirectly using wireless links) to appropriate location using e.g.; internet links but any way is possible.

The embedded and decentralised analysis

The electronics programmable systems (which could be modified after downloading from the ground) make a first data overview and estimate how and when to send signals to base station to get the best quality of results transmitted. The sampling rate has a several hundreds of Hz frequency.

Algorithms of data processing are based on different kinds of signal processing analyses.

Fast Fourier Transform (FFT), matching pursuit, wavelet and Prony method are the basic data processings used to find out appropriate data to evaluate, events based on ambient movement:

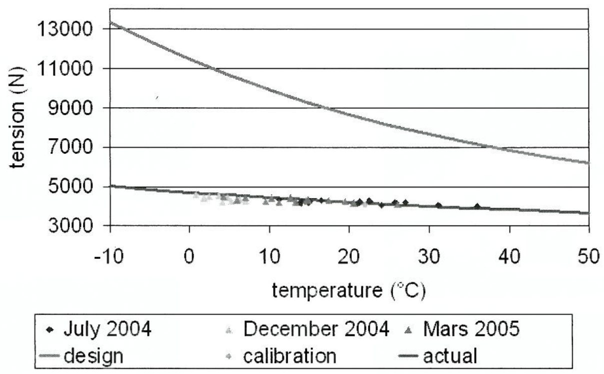

Figure 18: Mechanical tension – versus conductor temperature relationship in the dead-end span of 70 kV line under permanent monitoring during 15 months from June 2004 to to-day. Only few dots reproduced, including one calibration value. Upper curve is "as design" and lower curve (which fits the measurement dots) is as actual.

- ampacity;
- span movement in 3-D;
- vibration overview;
- ice loading in process;
- tower stiffness;
- fast transient due to impact or wire breakage.

Cable dynamics is deeply investigated based on existing theories and long experience in the field.

One extremely interesting feature in relation with ampacity is that such system has a direct real time evaluation of sag based on appropriate frequencies analysis, which has never been the case with existing in-span devices applied in power system analysis, like the M.W. Davis.

Some other sag determination methods based on temperature measurement or tension measurement may be very much disturbed by unknown effects like: temperature repartition along spans, actual mass, span length, effects of different dilatation coefficients in the same conductor (bimetallic, high temperature conductor, etc..), creep effect, presence of wind (not constant along the span, solar heating, emissivity coefficient, ... Moreover conductor radial thermal gradient may seriously alter the evaluation of the sag based on conductor surface measurement.

As sag may be deduced repetitively in different ambient conditions, a follow-up is easy to manage. The system may be installed in any place of the span to detect the basic sag.

As an example of first year of use on 70 kV line, the Fig. 18 shows some of the observed sag values at different conductor temperature. The shift between "as designed" tension-temperature relationship and "actual" is particularly impressive in this case. There is one dot on the actual curve (big round) obtained by laser measurement on site under known conditions of load, external temperature, solar heat and wind speed (very low). That calibration dot perfectly fit with our measurement.

Conclusions

Real time measurements and their possible insertion in the global management of power system networks is a key domain for the future network operation and control. This has been enhanced by recent liberalisation, public concern about new lines installation which forces to use existing lines at their maximum possible load, and the huge extension of OHL kilometres in very fast developing countries as China and India.

In the past, most of existing devices worked by their own , most often using batteries and having several months autonomy. They were placed on towers, suspension insulators or on the ground near the lines. Actually there is a trend of using in span multifunctional system, fully autonomous with direct sag and movement evaluations. They are linked to Internet giving access to the data in real time for helping decision (power flow redirection, predictive maintenance ...).

No doubt that such techniques will see rapid growth in their use, their development, their liability and robustness. There is a real challenge to use such system in harsh environment (strong electric and magnetic field, meteorological conditions including ice and wind as well as very cold to very high temperature), in some aspects close to spatial satellite constrains. The necessity to get low weight system (not to disturb the line or the phenomenon under supervision) is an extra constraint which is certainly not an easy task and need engineers team with a very wide skilled experience in different fields like microelectronics, microwaves, power system, mechanical and fluid dynamics, material knowledge, electromagnetic compatibility and large experience in packaging.

The knowledge exchange between different fields of health monitoring is an encouraging domain to learn from each other and conferences like Cable Dynamics will help solving these particularly difficult challenges. Last cable dynamics conference has been held in Charleston, SC (USA) last September 19-22, 2005 and this paper was presented as invited lecture. (more available on http://www.conf-aim.skynet.be/cable/index.html)

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[2] Part I: IEEE Trans on PAS, vol. PAS-96, No. 3 May/June 1977, pp 803-809

[3] Part II: IEEE Trans on PAS, vol. PAS-96, No. 3 May/June 1977, pp 810-825

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[5] Part IV: IEEE Trans on PAS, vol. PAS-99, No. 6 Nov/Dec 1980, pp 2184-2192

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Acknowledgement

The Ampacimon team would like to kindly acknowledge for the 70 kV line real time monitoring, ALE (Association liégeoise de l'électricité, Liège, Belgium), in particular Daniel Dejong and Robert Grooten for their kind assistance in using their line and making their staff available for installation.

The same team also acknowledge for the 220 kV line real time monitoring, ELIA (the Belgian GRT – gestionnaire du réseau de transport), in particular Eric Cloet for his kind assistance in using their line and making staff available for installation.

The team Ampacimon also kindly acknowledge the team of Pr Arnould (University of Liège, geometrology) for their kind assistance in laser measurement and then calibration of our system on the 70 kV line of ALE.

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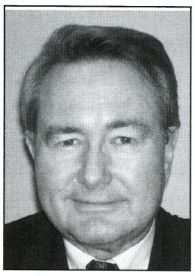

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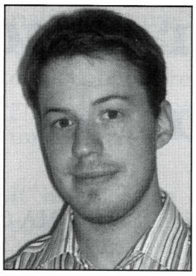

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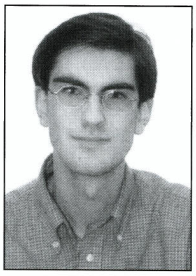

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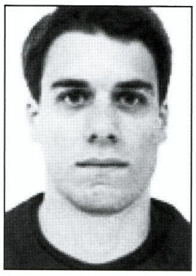

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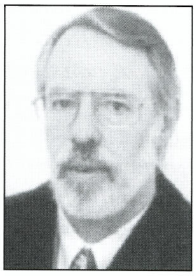

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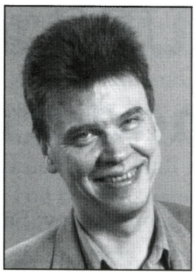

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