INTEGRATION OF SATELLITE TECHNOLOGIES AND LEARNING TECHNIQUES FOR WIDE AREA POWER LINES THERMAL PROTECTION

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ABSTRACT

This paper proposes an adaptive identification architecture for dynamical power lines thermal protection.
The proposed solution combines knowledge coming from expertise with empirical evidence provided by observations. This is performed by integrating an analytical thermal model, which estimates qualitatively the conductor hot spot temperature, and an adaptive corrective algorithm aimed at enhancing the estimation accuracy. The corrective algorithm is continuously adjusted by field data acquired through distributed fiber-optic sensor based on stimulated Brillouin scattering (SBS). The proposed architecture has been deployed on a hardware microcontroller equipped by satellite based communication system. The main results of experimental studies obtained on a laboratory overhead line are presented and discussed.

INTRODUCTION

The safeguard of power lines is assuming a major role in the deregulated market of electricity, where a malfunctioning power system could be responsible for serious damages to a large number of system operators having access to the shared energy resource.
The need of providing a reliable and safe service has historically induced the asset owner to adopt a conservative strategy in loading power lines. This worst-case approach decreases the risk of malfunctioning at the cost of a reduced power transfer capability. As a consequence, the conservative approach appears to be inadequate in the new competitive scenario where the strive for larger profits asks for pushing to the maximum the exploitation of plants. In this scenario, a reliable assessment of load capabilities and an effective management of the associated risks appear to be crucial [1-3].
The problem of supplying energy is time-varying in nature and demands therefore a dynamic solution in order to manage loading risks especially in the presence of contingencies.
In power lines, an accurate prediction of the hot spot temperature evolution represents an essential information to evaluate effectively the risk associated with a loading policy. This demands the design of a thermal model able to predict, given the actual conductor thermal state, the expected load level and the forecasted environmental conditions, the evolution of the hot spot temperature and the related maximum duration. The thermal model should also exhibit adaptive features, to deal with the intrinsic time varying phenomena affecting the thermal exchange characteristic of the conductor, and low computational requirements in order to assure an effective hardware implementation [4,5].
To address this problem the paper proposes the integration of physical model with adaptive learning techniques. This integration is obtained by using an analytical (or white-box) model of the hot spot temperature and an adaptive corrective (or black box) algorithm aimed to enhance the estimation accuracy. The black-box corrective algorithm considered in this paper is a non-linear adaptive technique based on the local learning theory [7,8]. This algorithm is continuously updated by experimental data coming from an hot spot temperature acquisition module, based on fibre optical temperature sensing technology.
The prediction model is implemented on an hardware microcontroller equipped by advanced communication services.
The microcontroller should enable the development of a client/server based architecture composed of a network of intelligent units remotely controlled by satellite based communication services. The units, installed in the most critical sections of the electrical network, assess dynamically the load capability of the main power lines and communicate the corresponding results to central servers for further post processing activities. We define e-assessment the monitoring and control functionality emerging from this distributed assessment architecture.
This research activity addresses several issues in power systems, like the optimal power flow study, where load capability data could be used to establish flexible thermal constraints, and static security analysis, where the distributed local units could be applied to predict the impact of emergency load profiles on the network components.
Obviously the fully accomplishment of these functionalities requires the definition of a robust communication architecture suitable to assure the reliable bi-directional data exchanging between the central servers and the network of intelligent units.
To address this problem the paper the employment of satellite based technologies has been proposed. In particular we focus on the use of Low Earth Orbit (LEO) satellites (i.e. satellites characterized by an orbital period of much shorter than a day). This technology offers several intrinsic advantages such as minimum delay, multi-satellite handoff, extremely small antenna, lower power consumption [6].
The experimental results obtained shows as the upgrading of Distribution Management Systems with this satellite based e-assessment functionality could lead to a sensible improvement of safety and reliability of the infrastructures.

AN ADAPTIVE ARCHITECTURE FOR POWER LINES THERMAL PROTECTION

The semi-physical (a.k.a. grey-box) modelling approach pursues the integration of the physical knowledge available about the system with the additional information retrievable from experimental measurements [4,5,7]. Here, we propose a grey-box architecture to improve the accuracy of physical models in dynamic loading of overhead lines. The basic idea is to combine the prediction returned by a simplified physical thermal model with an adaptive black-box correction algorithm.

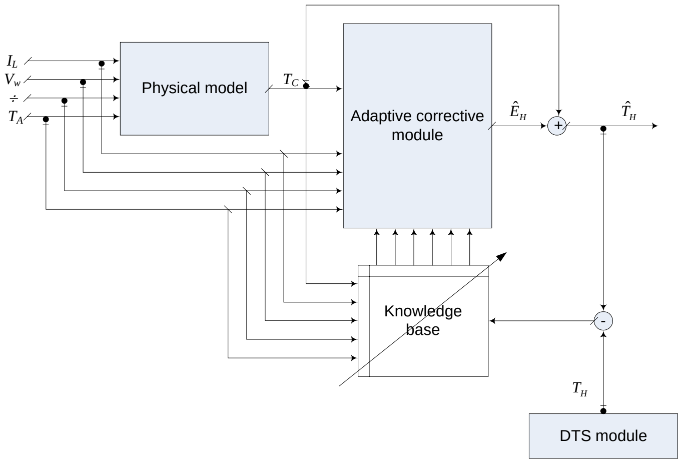

Figure 1 The proposed grey-box modelling architecture

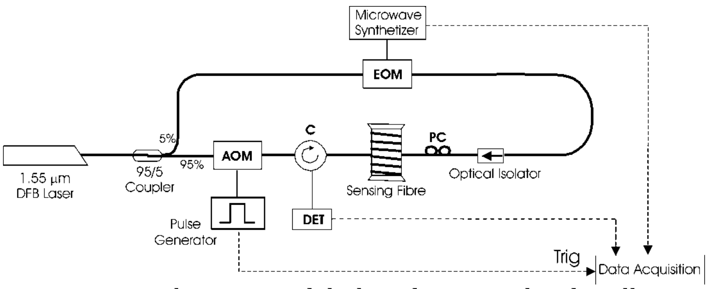

Figure 2: The DTS module based on stimulated Brillouin scattering. C = optical circulator , PC = polarization controller, EOM = electro-optic modulator, AOM = acousto-optic modulator, DET = photodetector

The proposed semi-physical architecture, sketched in fig.1, is made of four components:

- a DTS based measurement module that acquires periodically the conductors temperature profile along the line route;
- a simplified physical model (a.k.a. white box model) approximating the conductor thermal dynamics;
- an adaptive black-box model which corrects the white-box output: this is a predictive model which takes as inputs the white-box estimation and a set of observable variables (representing the conductor thermal state) and returns as output the correction term
- a satellite based communication module supporting the remote management functionalities.

This architecture is expected to be reliable both in terms of robustness and speed as it combines a fast built-in physical model and an adaptive dynamic corrector, sequentially updated by measured data, that adapts the whole architecture to "new" operating conditions. A way to detect a new condition is by checking regularly the prediction accuracy on fresh measurements: a prediction error over a fixed threshold could be used to trigger the update of the corrective model. It is worth noting also that this structure, by avoiding recursive feedbacks, should in principle also prevent stability problems and the consequent error divergence (frequent in recurrent neural architectures).
The following sections will address in detail the main features characterizing these four modules.

The DTS module

The DTS module integrated in the proposed architecture employs a "smart" overhead conductor containing temperature sensing fiber optics between the strands of the cable. The fibers, through a change in their optical properties, allow to acquire the conductor temperature profiles with extreme accuracy and, thus, to accurately determine the temperature at any given spot. This could lead to a potential increases in the line loading capability, as well as the early indications of pending temperature-related problems.
In details, the scheme of the DTS module employed is illustrated in Fig. 2. Light emitted by a Distributed Feedback (DFB) laser diode at a wavelength of 1550 nm is first split in two branches by a fibre-fused coupler. An acousto-optic modulator (AOM) provides pulses with widths down to 20ns (corresponding to 2-meters spatial resolution), whereas the CW probe signal is generated by the electro-optic modulator (EOM) using the sideband technique described in Ref. [9]. Basically, the lightwave exiting from EOM is frequency-shifted with respect to the pulse carrier frequency by a quantity equal to the RF frequency generated by the microwave synthesizer driving the EOM. In other words, the system is capable to provide two optical beams (one pulsed and one continuous-wave), being frequency-shifted by a quantity which can be scanned over an opportune range by varying the synthesizer RF frequency. The detector (DET) consists of an InGaAs photo-detector and a preamplifier with a sensitivity of 4mV/µA and an electrical bandwidth of 125MHz, whereas the data acquisition rate is 625MS/s. Distributed temperature measurements were carried out by setting an input pulse peak power of ≈ 3mW, and an input CW probe power of ≈ 25µW.
Data acquisition is performed by acquiring the time-domain waveforms related to the amplification of the probe power, for a number of pump-probe frequency shifts. The latter are varied by simply acting on the RF frequency generated by the microwave synthesizer. Hence, a sufficient number of time-domain waveforms are acquired for a range of pump-probe frequency shifts. These waveforms are then processed by fitting the Brillouin gain spectrum at each fibre section to a Lorentzian function. The central (peak) frequency of each Lorentzian curve provides an estimate of the local Brillouin frequency shift. As mentioned earlier, Brillouin frequency shift linearly depends on the local fibre temperature. Hence, the Brillouin frequency shift distribution along the fibre can be directly translated in a temperature profile, provided that a previous calibration of the fibre sensor had been performed.
For the temperature measurements presented in this paper, the entire process of data acquisition and processing required an overall time approximately equal to three minutes, so that a new temperature profile along the fibre was available every three minutes. The accuracy on temperature estimation was about ± 1°C, whereas spatial resolution was equal to two meters.

The physical model

The physical model adopted in the architecture is based on the calculation procedure proposed in [10]. This procedure is based on a simplified thermal equivalent model, and requires some specific characteristic data which can be affected by strong uncertainties [11]. It could therefore exhibit strong sensitivity to parameter variations.

Large uncertainties stem from several sources, depending on radiated heat loss and solar heat absorbed as a function of the line's operating voltage, conductor surface proprieties, level of atmospheric pollution, aging and so on [12].
All these uncertainties could considerably affect the thermal input model parameters and thus the final solution to a considerable extent. To address this problem the architecture employs a dynamic corrective module continuously adapted by the measured data coming from the DTS module.

The adaptive corrective module

The correction module is the black-box component of the grey-box architecture. This module takes as inputs the information coming from the physical model and the measured information coming from the DTS module. The expected output is a correction of the prediction returned by the white-box model.
Let $T_H^m(t)$ be the measured hot spot temperature at time t and $T_C(t)$ the prediction of $T_H^m(t)$ returned by the simplified physical model. We denote by $E_H(t) = T_H^m(t) - T_C(t)$ the white-box prediction error. Once $T_H^m(t)$ and $T_C(t)$ are available, the quantity $E_H(t)$ can be easily measured and stored in a training set. A black-box algorithm can be adopted to predict the value of $y(t) = E_H(t)$ according to the following formulation:

$$\hat{y}(t) = \hat{E}_H(t) = f\left(T_C(t), I_L(t-1), A(t)\right) = f(\varphi(t)) \quad (1)$$

where the input vector $\varphi(t)$ is composed by the temperature estimation $T_C(t)$, the expected load current $I_L(t-1)$ and the vector of forecasted weather conditions $A(t)$ (ambient temperature, solar heating and wind speed) .
The black-box algorithm proposed in this paper is based on the theory of local learning (i.e. the Lazy Learning algorithm) that, on a query-by-query basis, tunes the number of neighbours to be used in the local modelling process [8,12]. The algorithm adopted here proved to be successful in a number of academic and industrial case studies, ranging from time-series prediction to data modelling and non-linear control [13].

The satellite based communication module

The communication module allows remote users to employ the architecture services.
In this connection, amongst the possible solutions available, the employment of satellite based technologies appears to be particularly suitable since it could make possible the realization of advanced, high value communication services without requiring the construction of complex and expensive infrastructure and assuring, at the same time, a set of intrinsic advantages such as wide area coverage, easy access to remote sites, cost independent of distance, low error rates and adaptable to changing network patterns.
Moreover satellite based technologies are considered a key factor in lowering the degree of vulnerability of complex interactive networks and critical infrastructures as far as the electric power grids and transportation networks are concerned [6].
On the other hand the main factors that in the past have limited the application of satellite based technologies in power system communication have been recurring leasing cost of services and intrinsic time delay.
Nowadays the large number of satellite service providers in conjunction with the continuous lowering of the cost driving factors characterizing the new technologies are driving satellite communications to become competitive with other wireless based services. At the same time the recent launch of low earth orbiting (LEO) satellites, characterized by an orbital period of much shorter than a day, permits large reduction of communication time delay. These technologies have been successfully applied to support a wide range of advanced telecommunication services such as wireless internet and high-speed terrestrial/satellite networks.

EXPERIMENTAL RESULTS

The proposed architecture has been deployed on an Intelligent Electronic Device (IED) based on a ZWORLD-BL2100 unit, an advanced single-board computer that incorporates the Rabbit 2000™ microprocessor (operating at 22.1 MHz), 128K static RAM and 256K flash memory, 40 digital I/O channels, eleven 12-bit A/D converter inputs, four 12-bit D/A converter outputs, RS-232/RS-485 serial ports.
This IED has been equipped with a satellite based telecommunication system in order to assure the external connectivity required to support the remote management functionalities as shown on fig.2.
In this connection the QualcommTM GSP-1620 modem has been employed. This telecommunication unit, utilizes the satellite services proposed by the consortium Globalstar, that employ a constellation of 48 LEO satellites picks up signals from over 80% of the Earth's surface. It can handle both packet and asynchronous data connections. For packet data, it offers full duplex transmission and receives at a data port rate of 9600 bps using the Point to Point Protocol (PPP) as the transport mechanism for data packets. For asynchronous data, it offers full duplex transmission and receives at a Data port rate of somewhat less than packet data's 9600 bps, due to additional overhead for asynchronous data.
The software interface between the satellite based communication unit and the microcontroller have been programmed using an integrated development environment (Dynamic C™ premier).
The IED's performances have been experimentally assessed on a laboratory overhead line. The conductor temperature profile was acquired by the fibre-optics based DTS module described in section 2. The fibre employed as the sensor head was a standard, single-mode optical fibre, having an outer jacket diameter of 900µm and a total length of approximately 100m. A 30-meter overhead conductor containing the sensing fiber was employed.
In order to measure the load current, a Hall effect current transducer was used. The weather conditions (i.e. environmental temperature, wind speed and direction) were acquired from a meteorological station.

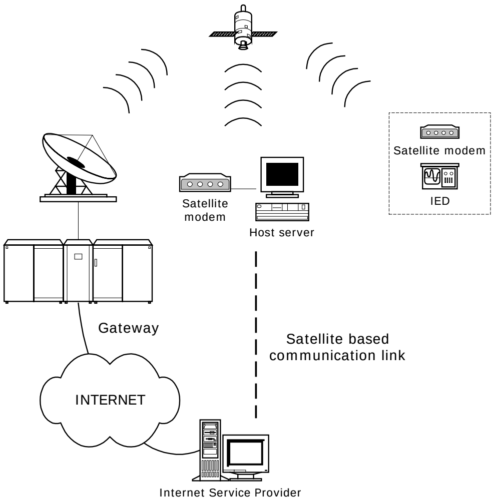

Figure 4: The communication architecture

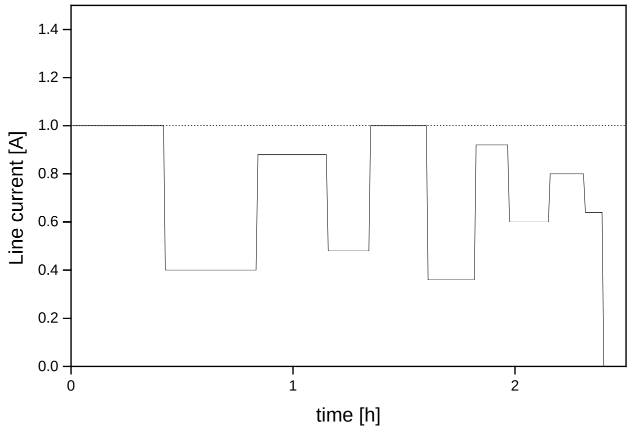

Figure 5: The load profile

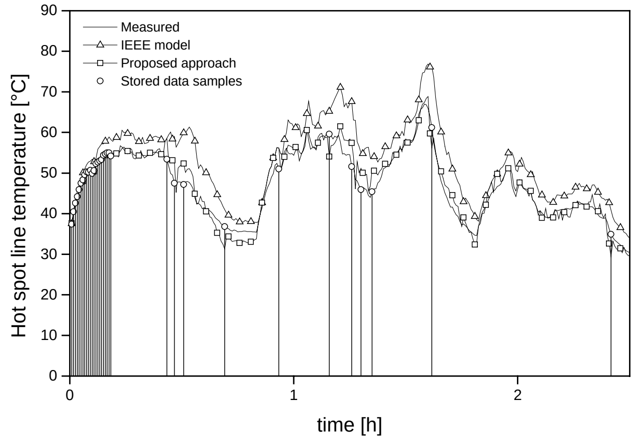

Figure 6: – Hot spot thermal prediction. First data set. The figure reports the real hot spot and the predictions returned by the white-box (IEEE) and the grey-box (proposed) models

All sensors were interfaced with a data acquisition unit, which was also used for controlling the line loading by a transformer tap-changer and a rectifier. A data logging system recorded the variables detected by each sensor at fixed time intervals. The measurement session consisted in loading the lines through various current profiles and in acquiring the corresponding conductor hot spot temperature. The adopted data set was recorded during 2.5 hours (from 12 am, 1-min sampling time) by loading the overhead line with the current profile reported in fig. 5, under variable weather conditions. The adopted load profile represents different operating conditions of the overhead line containing both situations of normal and high load conditions.

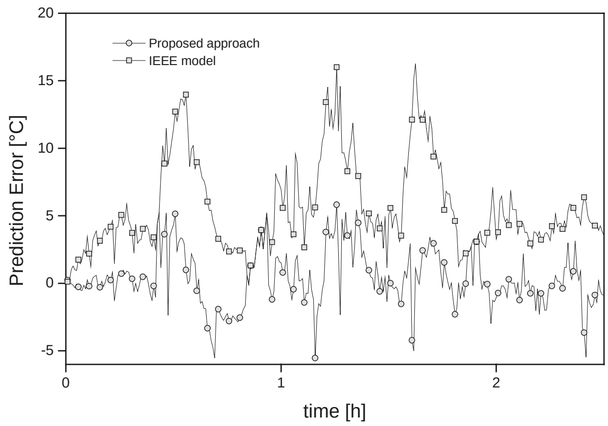

Figure 7: Prediction error profile

The obtained data set is composed of $N = 151$ input/output pairs where the first 22 are adopted for the initial predictive model tuning and the remaining pairs for validation purposes. All along the validation phase, an adaptation mechanism is kept activated. This mechanism updates the training set with the new observed input/output data each time the prediction error is worse than 5°C. The rationale for this sub-sampling is to store only those sample points that are relevant to the description of the system dynamic, discarding the ones that are redundant or less meaningful.

The results of the grey-box model on the data sets presented are reported in figs. 6-7.

In detail, fig.65 reports three curves for the first data set: the measured conductor hot spot temperature, the predictions returned by the white-box (IEEE) model and the one returned by the proposed grey-box model. Fig. 7 reports the corresponding prediction errors.

Analysing these figures, it is worth observing that the proposed methodology predicts the conductor hot spot temperature with a good degree of accuracy, compared to the solution computed by applying only the physical model. The high precision exhibited by the grey box model is made possible by the generalization capability of the corrective algorithm which returns a suitable hot spot temperature prediction also for highly variable load patterns. The need for algorithm tuning has been detected only in 11 operating points where it was necessary to adjourn its knowledge base by new data samples.

Further experimental activities have been devoted to assess the performance of the satellite based communication module. In this connection several figures of merit have been considered. They comprise in particular the degradation of services, and the data latency.

As far as the degradation of the service is concerned, the Frame Error Rate (FER), that is a measure of the radio link

quality, has been evaluated. The FER exhibited by the GAI (Globalstar Air Interface) traffic channel is of the order of 1% to 3%.
The data latency of the satellite based data link has been analyzed by connecting the IED to the Internet by the Globalstar satellite gateway and considering several web based connections for the host server. Thanks to the adoption of these facilities the data latency of the satellite data link has been estimated measuring, for a fixed time period, the packet round trip times at the transport level of the ISO/OSI stack. The statistical characterization of the measured time delays for the considered case studies are summarized in tab. I.

TABLE I
MEAN RESULTS

Case 1: IED managed by LEOS		
Trials number	250	
Estimated times for a complete packet route	Min.	1082 ms
	Max.	2794 ms
	Mean	1373 ms
Packet loss	25%	
Case 2: IED managed by GPRS		
Trials number	250	
Estimated times for a complete packet route	Min.	1347 ms
	Max.	4042 ms
	Mean	1962 ms
Packet loss	1%	

Analyzing this data it is worth observing that the satellite based connection compared to the GPRS has exhibited lower mean delay times but higher levels of lost packets. These performances could be improved connecting the host server to the internet by the same gateway adopted for the remote IED.

CONCLUSIONS

The changing scenario in the energy market asks the asset owners for new power lines loading strategies in order to attain high profits without losing reliability and security.
This work shed light on an adaptive architecture, based on semi-physical modelling, that aims to integrate knowledge coming from the expertise with empirical evidence provided by observations. The proposed architecture has been deployed on a micro controller-based unit in order to develop an advanced overloading protection unit.
The performances of this unit has been experimentally assessed on a laboratory overhead line. The obtained results are very promising.
The availability of sophisticated micro controller based protective units opens the ways to interesting future scenarios like Distribution Management Systems featuring advanced functionalities like remote control, monitoring and assessment (e-assessment). Moreover a diffused adoption of these micro controller units, equipped with reliable predictive models, could ensure a capillary assessment of the overall network capability rising the operative margins especially during emergency conditions.

REFERENCES

[1] G. Nokes, "Optimising power transmission and distribution networks using optical fibre distributed temperature sensing systems" *IEE Seminar on Asset Management of Cable Systems*, London, February 2000

[2] J.S.Lyall, G. Nourbakhsh, H.C. Zhao , "Underground power cable environment on line monitoring and analysis", *Proc. of 2000 Power Engineering Society Summer Meeting*, Seattle, Washington, 2000, pp.457-462.

[3] Study Committee 23-CIGRE', "Dynamic loading of transmission equipment", *Electra*, No. 202, Jun 2002, pp. 63-73.

[4] G. Bontempi, A.Vaccaro, D.Villacci,:" A semi-physical modelling architecture for dynamic assessment of power components loading capability", IEE Proceedings - Generation, Transmission and Distribution - Volume 151, Issue 04. July 2004,pp.533-542.

[5] D.Villacci, G. Bontempi, A.Vaccaro, M. Birattari:" The role of learning methods in the dynamic assessment of power components loading capability". IEEE trans. On Industrial Electronics Volume 52, Number 1, February 2005.

[6] A. Vaccaro, D.Villacci: "Performance Analysis of Low Earth Orbit Satellites for Power System Communication" Elsevier-Electric Power System Research Vol 73/3 pp 287-294, March 2005

[7] Lindskog, P. and L. Ljung, "Tools for semiphysical modelling" *International Journal of Adapt. Control Signal Process*ing, Vol. 9, No.6, Dec. 1995,pp. 509-523.

[8] E. Bertolissi, M. Birattari, G. Bontempi, A. Duchateau, H. Bersini, "Data-Driven Techniques for Direct Adaptive Control: the Lazy and the Fuzzy Approach", *Elsevier-Fuzzy Sets and Systems*, Vol.28, No.1, 2001, pp.3-14.

[9] M. Niklès, L. Thévenaz, , P. Robert, "Brillouin gain spectrum characterization in single-mode optical fibers", *J. Lightwave Technol.*, Vol.15, No.10, 1997, pp. 1842-1851

[10] IEEE, "Calculation of bare overhead conductor temperatures", Std. 783-1993.

[11] A. Piccolo, A. Vaccaro, D.Villacci: "Thermal rating assessment of Overhead Lines by Affine Arithmetic" *Electric Power Systems Research* vol. 71(3) pp.275-283, November 2004.

[12] Wan, H.; McCalley, J.D.; Vittal, V., 'Increasing thermal rating by risk analysis', IEEE Transactions on Power Systems,1999, 14(3), pp. 815 –828G. Bontempi, "Local

[13] Learning Techniques for Modelling, Prediction and Control" PhD dissertation. IRIDIA- Université Libre de Bruxelles, Belgium,1999.