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Experiences of the Belgian and French TSOs using the "Ampacimon" real-time dynamic rating system

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SUMMARY

Growing demand for power is a major challenge for grid operators worldwide, who are all finding it near impossible to build new lines. Because of this, transmission system operators (TSOs) must explore the idea of increasing the capacity of the existing transmission lines. One way to do this is to maximise the use of the conductors on the towers.
To this end, Elia - the Belgian system operator - decided to take part in the Ampacimon project (short for ampacity monitoring), launched by the University of Liège. French system operator RTE also showed strong interest in the project and decided to follow it up in collaboration with Elia and ULg.
To identify the optimum load for their HV lines, TSOs require a reliable dynamic rating system which is easy to install. This article documents TSOs' use of the Ampacimon innovative rating system to determine line ampacity.
The Ampacimon system measures the sag of an overhead HV line in real time. The sag – resulting from load and ambient factors such as temperature, wind direction and wind speed – is determined only by measuring conductor vibrations.
Conductor vibrations are measured using accelerometers. Conductor sag is calculated based on these measurements using data processing (fast Fourier transform) and simple mathematical formulae Once the sag is determined, a special software application can be used to calculate the line's maximum permissible current and make appropriate forecasts.
A number of measurement modules have been fitted on the HV grids operated by Elia and RTE. Experience has clearly demonstrated that conductor sag is highly variable and heavily dependent on local weather conditions. The Ampacimon real time monitoring system has been proven to be accurate with a sag error margin of 2% which is consistent with a safe real time operation of the instrumented lines.

KEYWORDS

Ampacimon – Real-time monitoring – Dynamic Rating – Conductor – Power Lines – Elia – RTE

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Importance of real-time dynamic rating systems

Overhead conductors are susceptible to ambient conditions such as air temperature, intense solar radiation, wind speed and wind direction, all of which can vary from one point along a line to the next. As such, the position of conductors can change, affecting a line's vertical safety clearance and subsequently its thermal rating. Moreover, the factors affecting the thermal rating of a line are difficult to predict. Consequently, estimates to determine the maximum permissible current for transmission lines have been conservative (for instance, the NBN C34-100 norm is used in Belgium). Energy fluxes in north-west Europe are becoming more widespread and unpredictable. Trading means that line loading has increased beyond expectations. Because of Belgium's central position in Europe, this is a recurring issue on Elia's grid. In addition, due to environmental constraints, it can take between 4 and 10 years to receive permission to build a new line. As a result, TSOs must explore the idea of increasing transmission line capacity by maximizing the use of existing conductors on towers.
To identify the optimum load for their HV lines, TSOs require a reliable dynamic rating system which is easy to install. For that reason, Elia (Belgium) and RTE (France) decided to experiment the new Ampacimon system on their grids.

Smart sensor "Ampacimon"

Ampacimon (fig. 01) is a smart sensor which is attached directly to an overhead power line. It can evaluate a span's real-time sag without the need for any supplementary data (such as load, sagging data, topological data, conductor data and weather data).

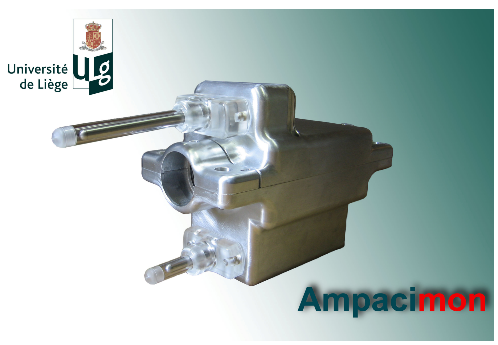


Fig. 01: Ampacimon module (or sensor) as installed on the RTE and ELIA grids

Ampacimon is a patented and a registrated trademark device that analyses conductor vibration and detects a span's fundamental frequencies. The fundamental frequencies form the exact signature of the span's sag. A greater sag means lower frequencies and vice versa. Exterior conditions (load, weather, topology, suspension movement, creep, presence of snow/ice, etc.) all affect sag and are therefore automatically incorporated into frequency readings. Ampacimon is a direct sag evaluator. Modules can be installed anywhere along the span. Using accelerometers, even a slight movement of 1 mm can be detected at the lowest frequency for a typical span (say 0.15 Hz), with even lower movements detectable at higher frequencies. Data is initially processed by a data signal processor (DSP) before being sent via GSM/GPRS to a remote server, where it is collated and analysed to give the appropriate readings.

Once the Ampacimon unit is installed on the span, it is powered by the local electromagnetic field and is thus autonomous. Furthermore, it does not need to be calibrated as sag is deduced from the detected frequencies, not from signal amplitude. Modules measure around 40 cm in length and weigh

approximately 8 kg. They are fixed to HV conductors and can be installed live-line in less than an hour.
A number of Ampacimon modules have been fitted to RTE's HV grid (fig. 02-03) and Elia's HV grid (Fig. 04-05) and a whole system has been developed that includes transmission and links with the control centre.

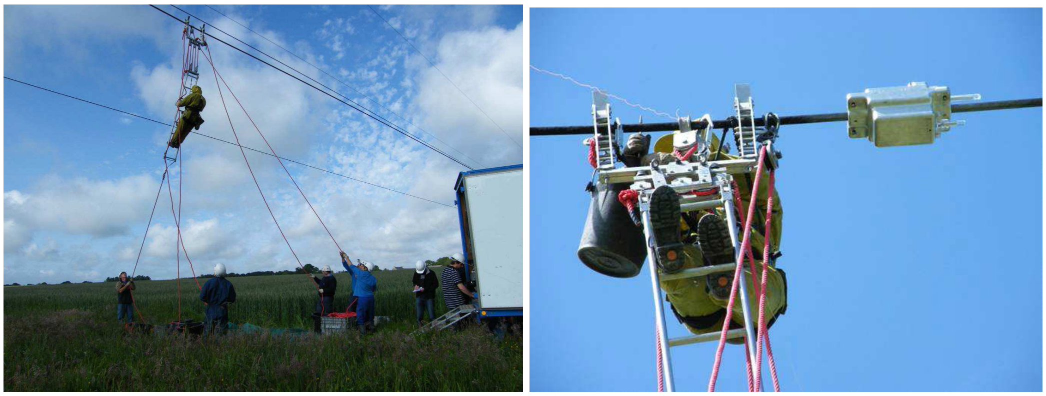


Fig. 02-03: 225 kV live-line installation of Ampacimon (June 2009) on the RTE grid

Fig. 04-05: 400 kV off-line installation of Ampacimon (July 2008) on the ELIA grid

Sag check

Independent land surveyors measured sag at a given point over a period of 4 days between June and November 2009. Measurements were taken from 5 spans where Ampacimon was installed.
Ampacimon output data was sent to RTE on the day and at the time of measurement then used to create figure 06. Measurements showed a margin of error of around 20 cm, which was accurate enough to predict ampacity.
Errors resulted from:

- The land surveyor's exact measurement time (margin estimated at 2 minutes)
- The accuracy of the land surveyor's measurement (margin estimated at 1%)
- The Ampacimon unit's exact measurement time (margin estimated at 2 minutes)
- The accuracy of the Ampacimon unit's measurement (margin estimated at 20 cm)

Based on these readings, we can confirm that Ampacimon gave appropriate and highly accurate sag measurements across the whole range from 0 to 25 m (less than 20 cm margin of error).

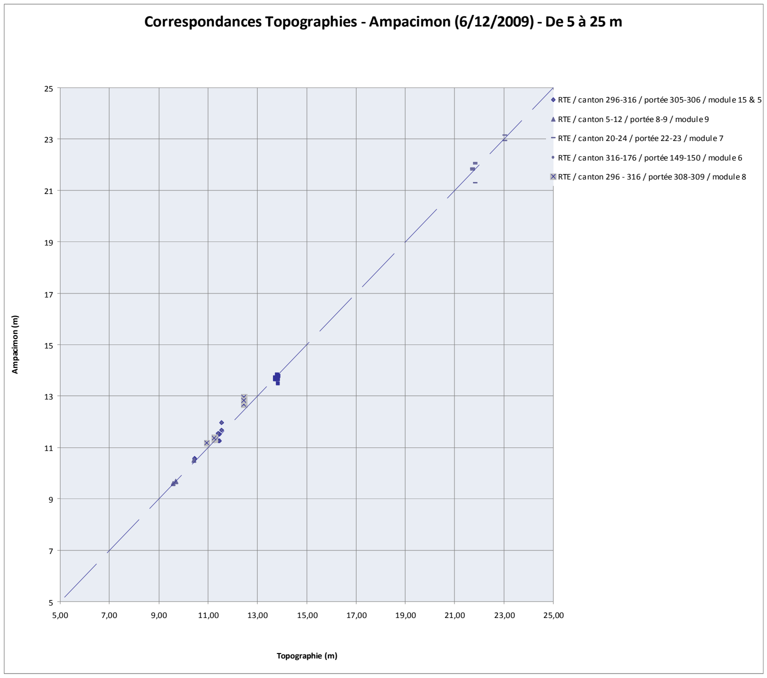


Fig. 06: sag measured by Ampacimon (ordinates) versus sag measured by land surveyors (abscissa)

Calculation of the ampacity

Real-time power line ampacity is calculated in three steps. The ruling span concept (CIGRE, 2007) is used to extrapolate the sag in one span to other spans.

- Step 1: evaluating actual sag conditions (carried out regularly but not in real time)

So called "state change equation (SE)" (fig. 07) is a relationship between sag and conductors mean temperature of the ruling span length. That equation has a "SE constant" which fix the sagging condition. Actual data may not fit with "as design" SE constant. Step 1 is used to define "actual" SE constant. This needs two synchronous inputs: sag and mean temperature as shown on figure 07.
The calculation of "SE constant" is made at appropriate times using recorded weather data, allowing prevailing conditions to be known when the sag is measured (by the sensor). Load readings are also essential and are provided by the TSO at the same times.
Actual weather conditions are difficult to measure accurately as ruling-span data can encompass a line of several kilometres in length. Different methods can be employed, some of which were discussed in (CIGRE 2006). As local weather can vary dramatically from one position to another, we recommend carrying out step 1 at night (no solar heat) with moderate (means not too small) and constant wind speed roughly orthogonal to the span where the sensor is installed. Local weather stations and/or more sophisticated systems can be used, but a cost/benefit analysis would need to be provided along with an efficiency evaluation (including the availability of new data, difficulties in installing the relevant systems (energy requirements, vandalism), data for spans located a considerable distance from the critical spans and the validity of all data). The systems used by Elia and RTE and developed in this paper rely on existing airport weather stations providing their data for free on the Internet (for each test area, data was provided by two weather stations close to the sections of line in question).
Of course, there is a difference between the data provided by weather stations and the prevailing weather conditions along all spans at conductor level. For this reason, further reassurance is needed. Fortunately, the data provided by the Ampacimon module (i.e. sag readings) is independent of any

other data. Step 1 converges after some days (rarely some weeks) to actual needed data (SE constant) to evaluate ampacity.

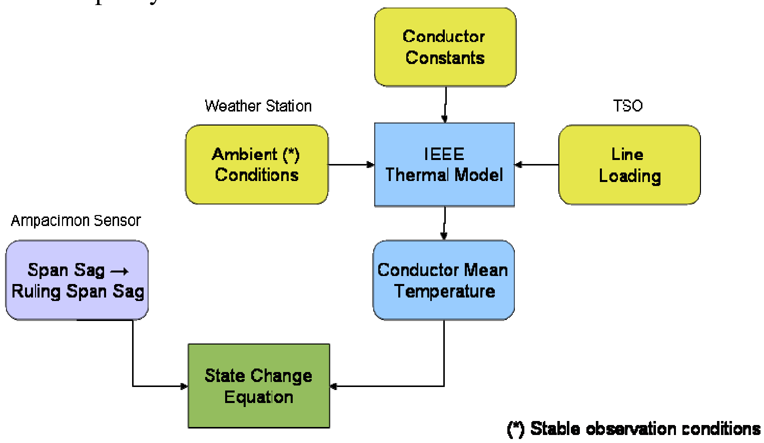


Fig. 07: determination of the actual line parameter ("SE constant" for state change equation constant)

- Step 2: real time effective weather conditions

This step is carried out in real time. Each time a sag measurement is provided by the sensor (typically every minute), the conductor mean temperature (on the ruling span) is calculated based on actual sag conditions and the state change equation (sag-temperature relationship). At this point, the IEEE,1993 or CIGRE,2007 thermal model can be applied and the actual weather data (based on measured values at sites near the line) are adapted to obtain the recorded sag (once again, line-load data is provided by the control center) as shown on figure 8.
Errors can occur during this step as the ruling-span concept has its own limitations. For this reason, a check is required at the next step.

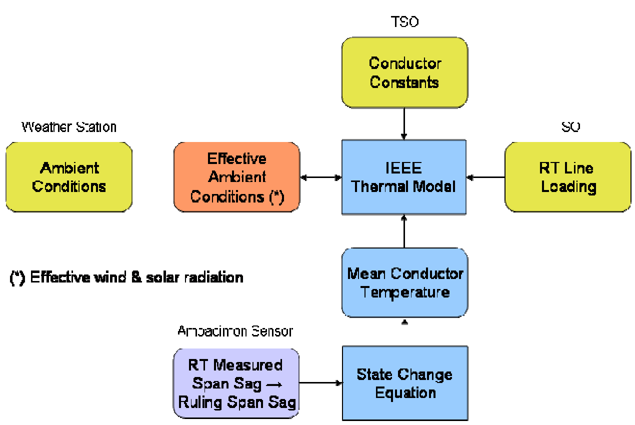


Fig. 08: looking for "effective" weather conditions which may justify actual observation

- Step 3: real time ampacity evaluation

Once the weather conditions which are to be used ("effective" weather conditions) are determined it is easy to apply the IEEE or CIGRE thermal model to determine the ampacity (fig. 09). The maximum permissible load is computed based on the worst conditions between the maximum conductor temperature (75°C in Belgium) and the maximum span sag converted into another maximum conductor temperature.

The ampacity is an approximation as some data e.g. weather conditions may be incorrect or poorly estimated. Once again, further reassurance is provided with Ampacimon sensor, by the fact that sag changes along critical spans are measured precisely and independently of any other data.
Moreover, using Ampacimon, if the actual sag reaches the maximum sag threshold (with a safe buffer), an alarm is triggered. At that time the ampacity evaluation is perfect and does not need any data.
Based on constant weather estimates, prediction of ampacity may be done in a similar way up to ten minutes or longer. This data is made available to dispatchers to help them make appropriate decisions.

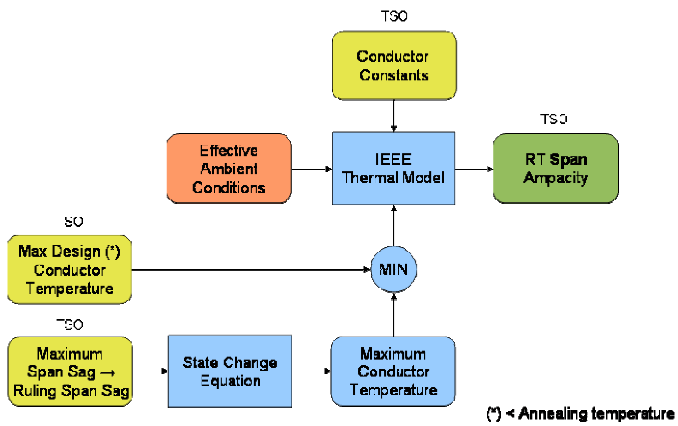
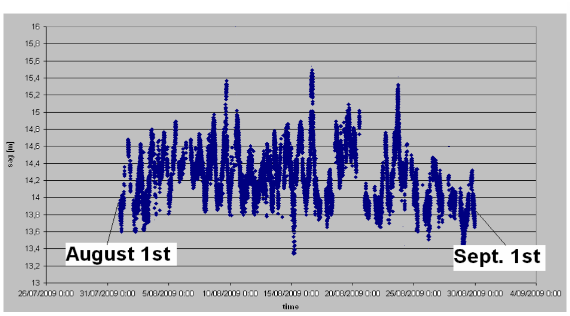


Fig. 09: the "effective" weather condition are used to determine the load transit that could lead to maximum available sag or maximum allowable temperature

Results on the ELIA and RTE grid

Figures 10 and 11 show the actual sag readings for an entire month. Maximum and minimum values may differ by as much as 2 metres for a sag of around 14 m in only one month..



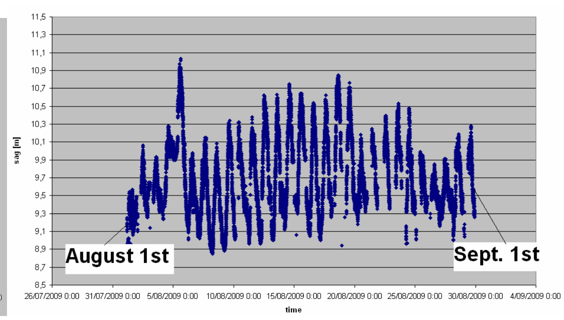


Fig. 10-11: sag evolution during one month at Doel-Zandvliet location (ELIA 400 kV) and near Nantes location (RTE 225 kV).

According to observations, sag changes are not only impacted by load changes but are, as one might expect, drastically affected by weather data. During the study period (July 2008 to November 2009) mean conductor temperature on the Elia line did not exceed 45°C on any given day and sag remained well within the stipulated maximum. Permissible ampacity was far higher than static ampacity (in most cases by at least 25%).

Figures 12 and 13 show an ampacity histogram for the HV lines of Elia and RTE.

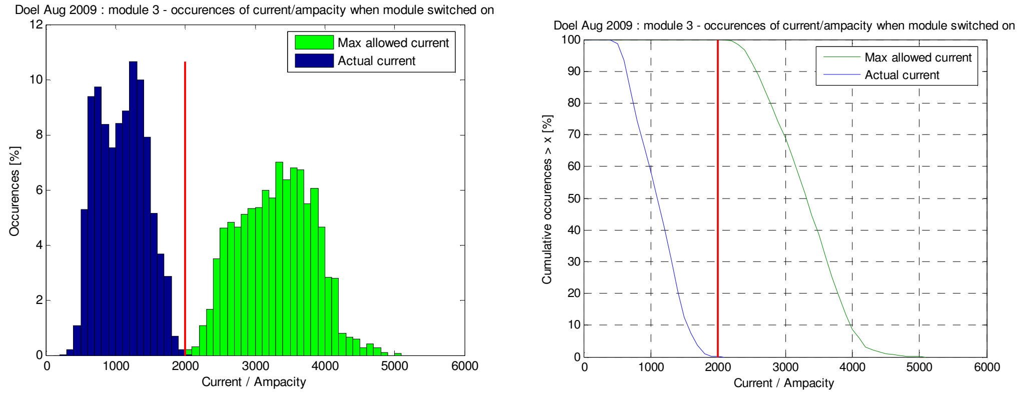


Fig. 12: ELIA 400 kV ampacity during August 2009 (twin bundle). Static rating at 2000 A. Occurrences and cumulative occurrences of actual current and available capacity

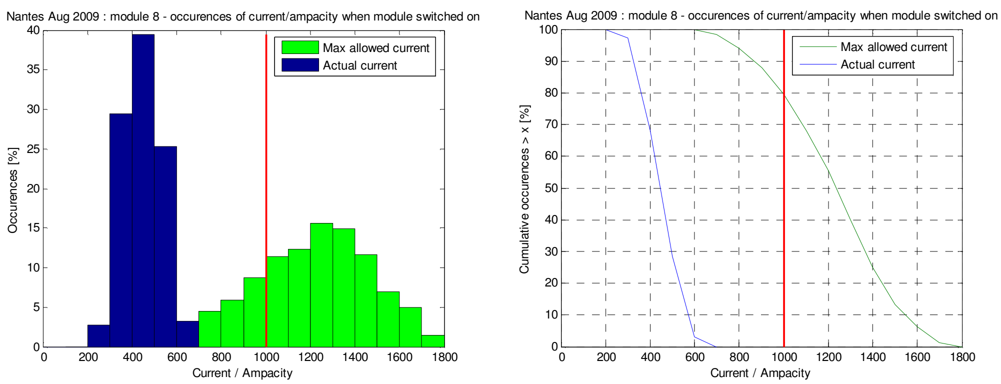


Fig. 13: RTE 225 kV ampacity during August 2009 (single conductor). Static rating at 1000 A. Occurrences and cumulative occurrences of actual current and available capacity

Of course, HV lines must be able to cope with a contingency situation (N-1). Based on observations, even in the most extreme cases, the contingency limit (which would typically exceed actual load by about 40% on these lines) would not have caused problems despite the static rating being exceeded by about 20% (in the case of ELIA). This means that, if there had been contingency situation, no lines would need to have been cut off. It also means that sensors have successfully reduced the risk of cascade failure and consequently black-out. Moreover, with HV-lines remaining in service during a contingency situation, there would have been no negative financial impact on power production relocation.
An example of ampacity layout at the control centre level is reproduced on figure 14.

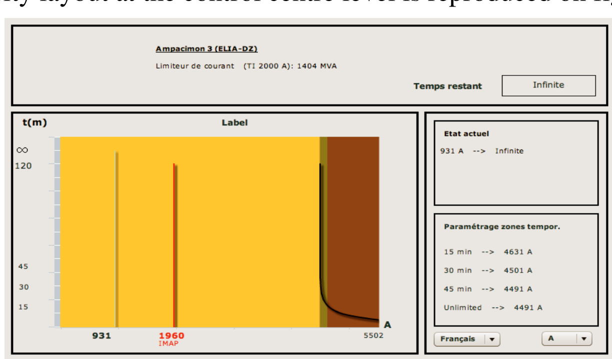


Fig. 14 Example of dispatcher layout (updated any 5 minutes) showing ampacity (asymptotic value) and ampacity available for short time

Impact of a real-time monitoring system

Some TSOs (e.g. RTE) operate the 400 and 225 kV grids based on permanent maximum permissible intensity levels calculated for homogenous areas according to climate and season. Based on conductor type, the region is split into different climate zones, each with one permanent permissible intensity level and two time-delayed permissible overload levels. Typically, for RTE, time delays are set at 20 minutes and 10 minutes. Seasonal operational procedures are based on a winter season (November-April), two intermediary seasons (April-May and September-November) and a summer season (May-September). In addition to the monitoring carried out by the operator from the control centre, protective mechanisms set to the various permissible intensity levels (permanent and time-delayed) trigger safety measures when system transmission levels exceed the permissible maximum. These fully automatic monitoring and protection systems guarantee the safety of individuals and properties if any given stresses are not dealt with by the operator within the stipulated time frame.
To set up a monitoring system whose maximum permissible intensity data varies significantly in real time, automatic protection systems must currently be disconnected. Indeed, automatic protection system thresholds cannot handle the variable reference intensity. To disable the emergency protective mechanisms to the aid of the operator, operating regulations need to be modified and operators must have complete trust in the monitoring system reporting the permanent permissible intensity level and the temporary permissible overload levels.
For control centre operators to build their trust in monitoring systems that modify established practices, discussions must take place on the pros and cons of RTM systems and on which spans to equip. Research must be carried out on which critical spans to equip before installing and operating a system. The operator’s knowledge of sag, and hence the distance between the line and the ground, is of the utmost importance if the system is to be run safely and securely, especially in cases where only a few spans are equipped to provide an overview of the system’s operation.

Carrying out a test phase over several months without real operational use is also an important step for operators to take. It allows a mechanism’s performance to be monitored by comparing recorded results with topographical data. As indicated below, ensuring compliance with safety distances is critical in system operation. The test phase also helps to guarantee that data acquisition and data processing methods are reliable, since such data is recorded over a period of several months.
After the test phase, the system has to be put into actual operation. Operational procedures must be modified and the unique characteristics of real-time monitoring mechanisms taken into account. The procedures must also allow standard operation to be resumed without system monitoring in case the mechanism is not available.

Practical experience

The findings from the test phase confirmed that monitoring mechanisms were reliable, especially in terms of the physical measurements for line sag calculations. Furthermore, comparing the findings with measurements from topographical data helped to determine the level of accuracy of the entire data acquisition and processing chain. The results are accurate enough for industrial use.
The provided data revealed that, more than 99% of the time, system transit capacity was higher than the limit set using traditional methods, including both deterministic and probabilistic methods. Therefore, using the monitoring mechanisms for overhead lines should allow optimal system operation in real time.
However, forecasting and controlling stresses must be prioritised over pure real-time data processing. Indeed, having early access (a day or several hours in advance) to information on system transit capacity for the relevant period can optimise the impact of temporarily implemented measures (e.g. non-operation of the group or group operation at minimum power). Only using system transit capacity data in real time makes it difficult to adapt prevailing measures and control stresses.
So, to be able to make full use of the data provided by real-time monitoring systems, these systems must be combined with a predictive mechanism to provide a forecast of the allowable capacity within a given time period (2-3 hours or the day before). The predictive mechanism must provide a forecast –

and a reliability rating based on the desired time-frame – using information provided by the monitoring system and local weather forecasts.

Conclusion

We know that the thermal rating of high-voltage (HV) lines varies continually but there is currently little information available on the dynamic load capacity of lines. Consequently, conservative estimates based on high solar heating, high external temperature and low wind speed are used to calculate permissible HV line loads.

Experience on the Elia and RTE grids shows that actual ambient conditions are normally less restrictive than those used in the theoretical calculations (see use of standards). This means that overhead lines could transmit more current than their predefined nominal value most of the time.

Practical experience shows that conductor sag is extremely variable and heavily dependent on local weather conditions. We are convinced that real-time monitoring and dynamic ratings enable optimum HV line operation, help to enhance grid security and potentially prevent blackouts.

If transmission system operators are willing to convert to smart grids, then new technologies will be critical. We believe that the Ampacimon system could form part of a 'SmartGrid' toolbox. Of course, transmission systems operators must be prepared to adopt their conventional working methods e.g. operating the grid in accordance with dynamic data based on weather conditions, and this may prove a very difficult step to take.

The Ampacimon system is ready for real-time application and further research is underway to achieve longer term predictions based on weather forecasts and historical analysis.

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