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New methode of temperature measurement of overhead transmission lines (OHTLs) utilizing surface acoustic wave (SAW) sensors

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Abstract: In the deregulated market of electric transmission power systems today and as the demand for energy continues to rise, electric utilities are faced with the challenge of moving more power over existing lines, while at the same time obtaining permissions for constructing new lines becomes increasingly difficult.

As a result, transmission system utilities and operators are currently looking for possibilities to maximize the capacity of the existing systems without increasing the risk for a system failure due to higher loading and an aged transmission infrastructure. One approach to manage the reliable operation of such systems is using modern monitoring techniques as means to prevent unexpected system outages. On overhead transmission lines the sag of the individual line is an operational measure as well as a security concern, which directly relates to the conductor operating temperature. The conductor operating temperature is influenced by various conditions such as line losses, ambient temperature, wind speed and direction, solar radiation and conductor material properties.

During periods of high ambient temperatures, low wind speed and high electrical system load conditions, monitoring and analyzing regional areas of the transmission network can be essential to evaluate the actual conductor operating temperature for the purpose of optimizing line capacity and to prohibit potential sag problems. For the determination of the conductor temperature various methods have been discussed recently. In the current contribution a method, basing on the well known SAW technology, is presented. The developed sensor, which is optimized regarding its dielectric, thermal and high frequency behaviour, could be fixed easily at the overhead line with helical clamps.

The sensor has a thermal behaviour different from the overhead transmission line. Due to the fact that the geometric and mass dimensions of the sensor are not the same as the dimensions of the line conductor, the measured sensor temperature will not be identical to the temperature of the overhead transmission line in the free span. For including this, an algorithm for the determination of the conductor temperature by using the measured sensor temperature is developed. Various algorithmic case studies examples and real laboratory measurements are discussed.

1 INTRODUCTION

The situation in the electricity market is changing in the last few years. On the one hand the electrical energy market in continental Europe was deregulated some years ago and on the other hand the electrical energy consumption is still increasing at an average level in Europe of approx. 2 % per year. Due to the deregulated electrical energy market the extra high voltage (EHV) transmission lines are more and more used as transportation utilities for the “delivery” of electrical energy across the European transmission network (UCTE).

Fig 1. EHV overhead transmission lines

Challenging for instance are situations where a lot of generation power is located in one part (e.g in the north of Germany), where power consumption is relatively low, while there is a bottleneck in the south of Europe (especially Italy). Furthermore less new OHTLs were built in the last few years, because it takes more time to fulfil the environmental and governmental laws. Additionally the regulated fees for energy transfer in the network decreases constantly. Hence the existing EHV overhead lines must sustain higher upcoming energy transfer at lower compensation prices. The EHV overhead transmission lines were mainly built in the early 60s and in the 70s of the last century according to the national and international standards. The sag of overhead lines are dimensioned at a specific temperature, which is commonly 60°C for standard ACSR (aluminium conductor steel reinforced) conductor, because the reversible tension of the conductor depends mainly on the temperature, when no additional external load eg. ice on the conductor is present. The rated current at a conductor temperature for e.g. 80°C is defined by specified environmental conditions like 35 °C, 0,6 m/s wind and usual solar radiation [4]. The approx. 40 - 50 years old aged conductors have been creeping by several mechanisms, which are discussed in several papers [5], [6].

In the past the grid was loaded with approx. 30%…50% of the rated current and the rated temperature was reached only in specific cases. But in the last few years the load of the OHTLs is increasing due to the above discussed points up to the rated values. Consequently the knowledge of the overhead line temperature is necessary for the decision of the possible transmission line loading. Due to the increasing load of overhead lines the sag is maximized and the clearance is minimized respectively.

Temperature measuring systems available for this purpose are rare and their practicability should be proven in field tests. Various systems need a galvanic connection to the sensor, which is not possible at high voltage overhead lines and other systems cannot cope with the wide range of the environmental conditions.

These problems can be overcome with the use of passive SAW sensors.

2 SAW TECHNOLOGY AND ITS APPLICATION FOR OHTL (SENSOR)

2.1. SAW Technology

The SAW sensors have been used for long term field tests in various applications in the field of high voltage engineering. The field tests with metal oxide surge arresters started 1997. Obtaining good results with this measuring technique the system was also installed at various OHTLs and substations. [1], [2]

2.2. Sensor antenna

The fixing position of the sensor is shown in Fig. 5 Due to line movements the sensor can move on an ellipsoidal curve, which can be in principle split up in two directions

- direction along the conductor, which can be influenced by sag variation, wind, temperature of the overhead line (approx. angle ±15°)
- direction perpendicular to the conductor, which is mainly influenced by wind (approx. angle ±45°)

For this situation an easy and robust suitable sensor antenna was developed with a gain of approx. 5 dBi and a beam width of approx. 60° x 60°. The polarization is vertical.

2.3. Sensor clamp for fixing the SAW sensor at OHTLs

For the mounting of the sensor with the antenna on an OHTL a special clamp was developed. The engineering requirements of the clamp can be summarized as follows

- housing of the sensor tag,
- housing of the sensor antenna,
- easy to install,
- long time stable connection.

According to these points a clamp with helical fixing is used for easy installing and reliable connection of the sensor clamp at overhead line. The sensor and the sensor antenna are covered by a PTFE (polytetrafluoroethylene) enclosure (Fig. 3)

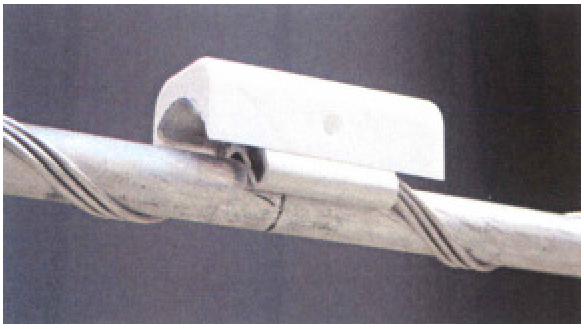

Fig 3 complete sensor wit antenna covered by a PTFE enclosure (with helical fixings)

This sensor was tested in a high voltage laboratory for fulfilling the national and international standards for RIV (radio influence voltage) according to IEC 61284 (requirements and tests for fittings), which passed the test for single line 123 kV and 245 kV and triple bundle conductor for 400 kV.

3 DESCRIPTION OF THE SYSTEM

The EHV overhead line online temperature monitoring system consists of a measuring unit at the tower, a database server at the e.g. substation and a data communication link.

3.1. Components at the tower

At tower the measuring unit is installed (fig. 5). Above the conductor the two tower antennas (transmitting and receiving antenna) must be fixed with a suitable orientation to the sensor by using a telescopic sight. The sensor is mounted at a distance of approx. 2 m from the fitting of the suspension string. The radar unit box is mounted close to the tower antennas to ensure an adequate high frequency connection with cables. For the power supply of the system two solar panels are fixed at the top of the tower. The central unit is installed at the bottom of the tower or at a specific height for protecting it from vandalism. The central unit consists of the batteries with power management, a controller board and the GPRS modem for data connection. The control unit is connected with the radar unit box by using fiber optic link cable.

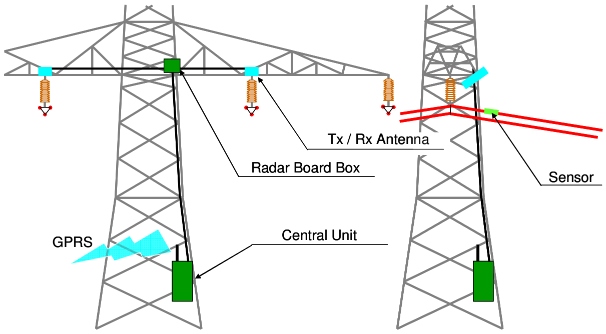

Fig 4 System components of the SAW temperature online monitoring system for HV lines at the tower

4 EXAMPLE FOR AN INSTALLATION OF THE SYSTEM

The first installations of this system were completed at the end of the year 2006. The data acquisition works stable at various environmental conditions e.g. at high wind, snow and rain fall or fog. Fig. 5 shows, an example for the installation of the RiTHERM temperature online monitoring system at a 400 kV line.

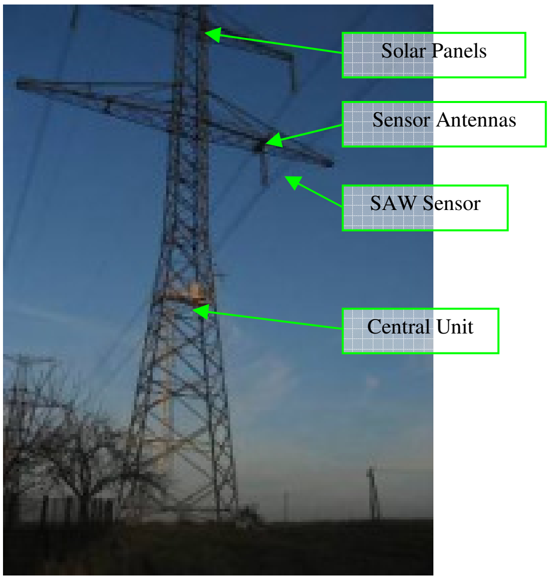

Fig 5 Example for the installation of the system

5 COMPUTATION OF THE CONDUCTOR TEMPERATURE

The measured sensor temperature different from the conductor temperature of the conductor in the free span due to the higher surface regarding thermal flow and higher thermal conductance of the sensor clamp.

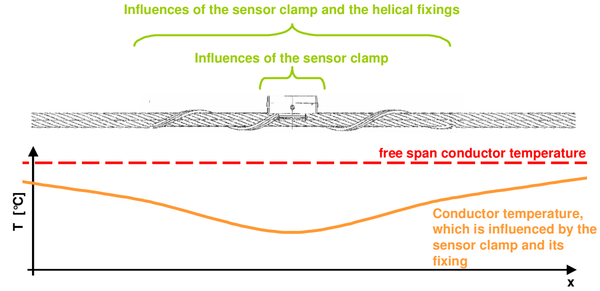

Fig 6 Locality distribution of the conductor temperature influenced by a sensor clamp – heat sink effect

5.1. Basics

Both, the sensor clamp and the conductor are influenced by the same surrounding conditions like ambient temperature, wind speed, wind direction, solar radiation and current. The measured temperature (which is the result of the thermal power balance of the sensor-conductor compound) of the sensor incorporates all of the same influences as the thermal power balance of the monitored conductor. But the thermal balance of incoming and outgoing thermal power and so the temperatures of the thermal system of the sensor-conductor compound and the conductor aren't the same.

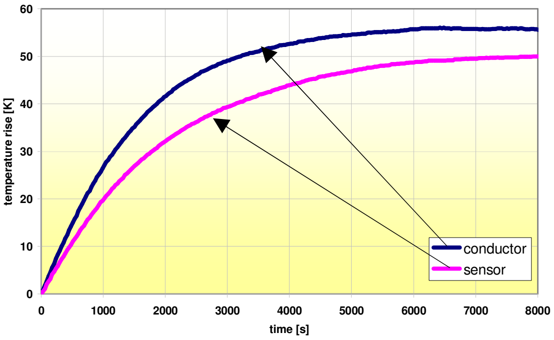

Fig 7 Differential between the temperature of the sensor (magenta lower course) and the conductor in the free span (blue higher course)

In general difference in both the dynamical and static time characteristic of the heating function can be recognized. A computation of the free span conductor temperature with a constant factor is hence not possible. The problem definition is how can the temperature of the conductor in the free span be calculated with the usage of the sensor temperature?

If the surrounding conditions like wind, wind direction, ambient temperature, solar radiation and current at the calculated point in the free span and at the sensor are the same or similar, it is possible to calculate the temperature by using following procedure: measuring of the sensor temperature at a specific time interval (which is smaller then the thermal time constant of the conductor, e.g. 60 s); calculation of the thermal equivalent thermal source; calculation of the free span conductor temperature.

For the basic consideration the thermal system is considered as linear, which needs to be enhanced for a real thermal system as discussed later. For such calculations the thermal behaviour of the system must be known by using e.g. thermal weighting functions.

A reduced network for the calculation of the equivalent thermal source is shown in Fig. 8.

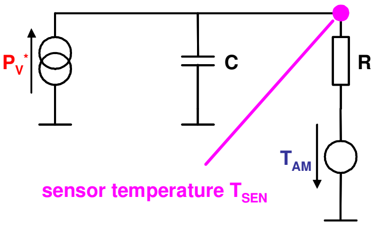

Fig 8 equivalent thermal network of the sensor

For the calculation of the sensor temperature $T_{SEN}(t)$ at a specific time point t the following equation (convolution integral) can be used.

$$T_{SEN}(t) = \int P_V^*(t-\tau)\cdot g(\tau)\cdot d\tau \qquad (1)$$

$P_V{}^*$ is the equivalent thermal source and g is the thermal weighting function. But for the necessary computation of the conductor temperature, T_{SEN} is measured and $P_V{}^*$ is the value, which must be computed.

This calculation is shown in Fig. 9, which is valid if some boundary conditions are fulfilled. At the timestamp t_0 a sensor temperature (the sensor temperature course for $t < t_0$ is known) is measured, the equivalent thermal source is known for $t < t_0$, the ambient temperature for $t <= t_0$ is measured and a thermal weighting function for the sensor-conductor compound and conductor is available from earlier experiments.

By using the data of the equivalent thermal source $P_V{}^*$ for the time $t < t_0$ and the shown weighting function the lower historical influenced value (lower green part) of the sensor temperature can be calculated. The difference between the historically influenced value (lower green part) of the sensor temperature and the measured sensor temperature at t_0 is affected from the changes of the effects during the last measuring interval. By using this difference the equivalent thermal source $P_V{}^*$ at t_0 can be calculated. The equation is shown as follows

$$P_V^*(t_0) = \frac{T_{SEN}(t_0) - \sum\limits_{i=0} T_{AMB}(t_0 - i\cdot dt)\cdot g_{AMB}(i\cdot dt)\cdot dt - \sum\limits_{i=1} P_V^*(t_0 - i\cdot dt)\cdot g_{SEN}(i\cdot dt)\cdot dt}{g_{SEN}(0)\cdot dt} \qquad (2)$$

where T_{AMB} is the ambient temperature, g_{AMB} is the weighting function for the behaviour at changes in the ambient temperature, g_{SEN} the thermal weighting function for the behaviour of changes in the thermal equivalent power source and dt the constant measuring interval like 60 s.

The initial value for the equivalent thermal source can be calculated with (2) assuming that the system is in steady state condition.

The stability of the calculation could be divided in two parts. First of all any convolution with bounded functions and input parameters are stable (bounded

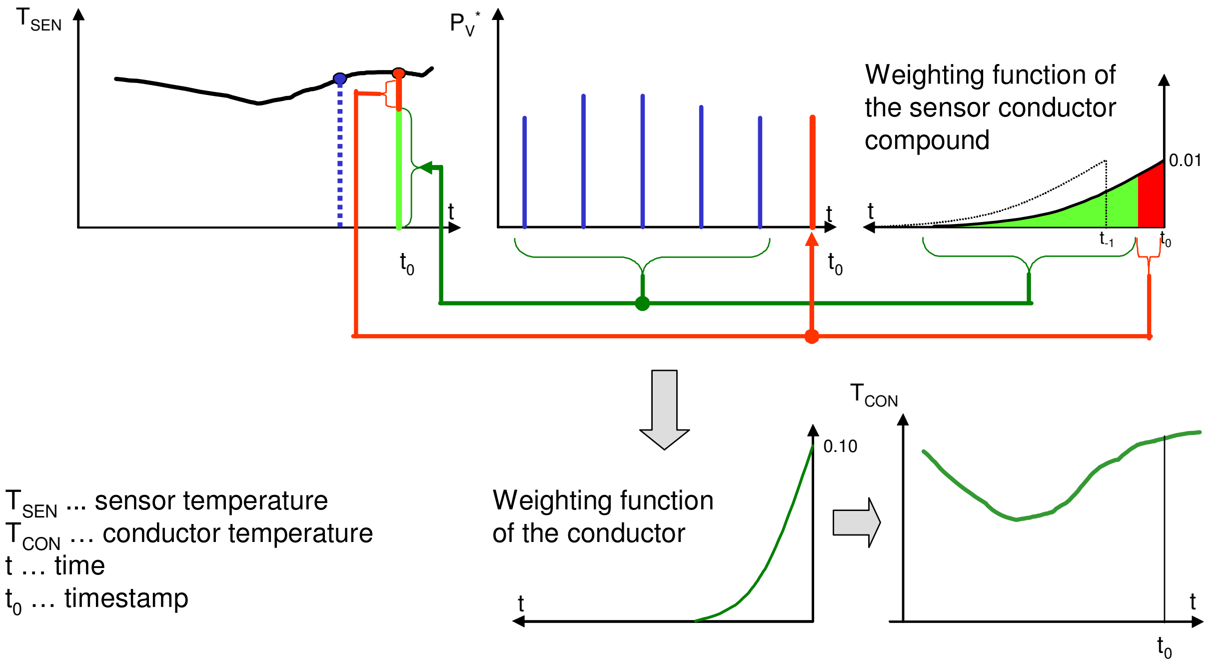

Fig. 9 Schematic of the free span conductor temperature computation

input bounded output - BIBO) and secondly the algorithm of the equivalent thermal source uses a feedback loop.

In the basic consideration of the description of the algorithm the equivalent network is assumed being linear. Therefore the weighting functions are independent of the temperature. The real thermal network of the sensor conductor compound and the conductor is not linear. Detailed investigations have been carried out to evaluate the influence of this non linear behaviour of the thermal system to the computation algorithm. According to these investigations the surrounding conditions for the determination of the thermal weighting functions for a secure calculation of the overhead line temperature in the free span are developed.

5.2. Determination of the weighting functions

For the calculation, as shown in the last section, four thermal weighting functions are necessary:

- Weighting function as a result of a power loss impulse at the sensor conductor compound,
- Weighting function as a result of an ambient temperature impulse at the sensor conductor compound,
- Weighting function as a result of a power loss impulse at the non-influenced conductor,
- Weighting function as a result of an ambient temperature impulse at the non-influenced conductor.

These four weighting functions must be determined for each sensor – conductor combination before the computation of the free span temperature of the conductor can be applied by using the measured sensor temperature with the SAW online OHTL monitoring system. The determination of the weighting functions can be made by arranging experiments or by using an equivalent thermal network, which must be calibrated by real experiments (Fig. 10).

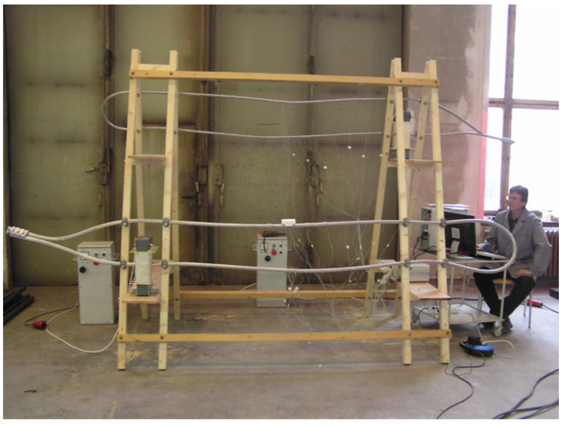

Fig. 10 Experiments at Dresden University of Technology

In Fig. 11 the measured temperature and the calculated temperature of a heating experiment is shown. The two functions do not show big deviations from each other.

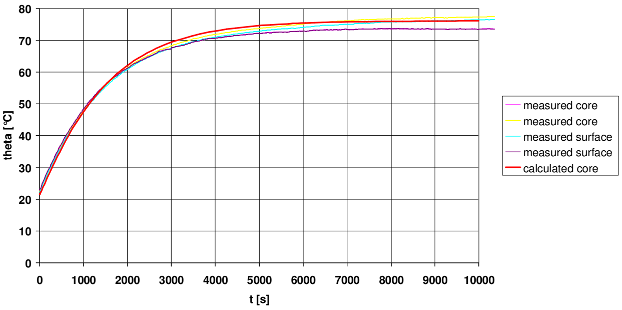

Fig. 11 Comparison of experiments and thermal simulations

Due to the strong dependency of the temperature of a conductor on the wind speed and direction ([7], [9], [10]) some wind channel experiments and investigations are made.

5.3. Example calculations

In the following section a calculation example is presented using the described algorithm and the weighting functions. In Fig. 12 the computed conductor temperature in the free span and the possible conductor temperatures at various surrounding conditions are shown. The sensor temperature for all experiments is the same that means that at higher wind speeds higher currents (higher Ohm's losses) are necessary.

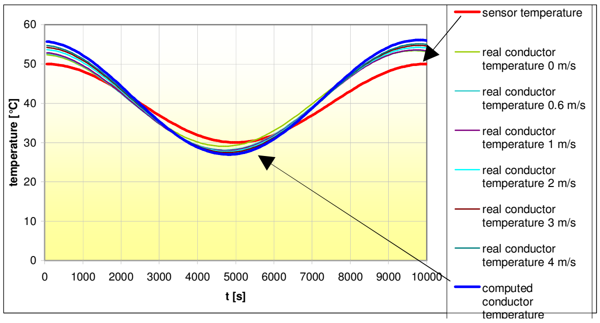

Fig. 12 Computed conductor temperature (thick line) in comparison with real conductor temperature at various wind speeds (thin lines)

The computed free span conductor temperature coincides sufficiently with the real temperatures at the shown surrounding conditions. Furthermore the estimated conductor temperature is slightly higher than the real temperature at the shown surrounding conditions. Consequently a secure temperature evaluation regarding the operation of the OHTL is performed.

6 FURTHER WORKS

This algorithm is tested in the laboratory and with various simulations. At first systems the algorithm behaviour is tested in field with the real micro climate surroundings of high voltage lines and will be further developed and adapted.

For the system operator and the load control the temperature of the overhead line is a helpful monitoring value. For controlling the load flow the time-dependent possible current for the OHTL depending on the computed temperature of the conductor in the free span is necessary. The load prognosis by using the computed free-span conductor temperature is also developed in further works.

7 SUMMERY

Due to the conditions at the changed market of electrical energy new monitoring systems for overhead lines are necessary. The well-known SAW technology can be used for a temperature-based application easily. The sensors are passive and can withstand the common transient and power frequency stress on an OHTL. For the usage at overhead lines a suitable clamp, which can be easy installed and which fulfils the mechanical and electrical requirements, was designed. The data acquisition unit was designed for the rough requirements of installations at EHV overhead line towers and get their power supply from solar panels. A method for the computation of the free span conductor temperature by using of the measured sensor temperature has been presented. The stability and the accuracy of the algorithm are tested in simulation and will be further developed by using the experience of the first installed systems. This online monitoring system could be fully used for the load monitoring and for optimizing the load of transmission lines and is thus beneficial in meeting new requirements in the changed market of electrical power engineering.

8 ACKNOWLEDGEMENT

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