Infrared spectral imaging for damage detection and prevention of overhead power lines

Gabriela Molinar and Wilhelm Stork

Karlsruhe Institute of Technology,
Institute for Information Processing Technologies,
Engesserstraße 5, 76131 Karlsruhe, Germany

Abstract A proposal for an overhead line monitoring system using infrared imaging is presented as a thermal characterization of a target far from the imaging sensor. The thermal image is used to measure the clearance from conductor to ground, which allows the transmission system operators to regulate the power transmission to prevent possible dangerous events. If the line is too elongated due to high temperatures, the possibility of electrical sparks with objects near the line increases. Additionally, this system can detect hot spots in the connectors and ice loads over the line if the position of the field of view is changed. The design of this system is described in detail, as well as some simulations and experimental results are shown to illustrate the capabilities of the proposed system.

Keywords: Overhead line monitoring system, infrared camera, clearance measurement, hot spot, ice detection.

1 Introduction

Electricity has become a basic need for the modern society and the electric network is used to transport it from power plants to consumers. This medium must be safe and employed in an efficient way for economic reasons. Therefore the transmission system operators (TSO) use monitoring systems to maintain the state of the transmission lines under supervision. Using sensors and optimal control, the capacity of the existent network can be increased up to 20 % [2], reducing the need to construct new lines [3]. Moreover, these monitoring systems help prevent premature conductor aging due to high temperatures or an electrical discharge with objects below or near the line (clearance to ground too low).

The state-of-the-art of overhead line monitoring systems (OLMS) shows different ways to measure the conductor parameters: Indirect methods, which use only weather data to estimate the conductor temperature, or direct methods, which include sensors installed on the lines, suffering from electromagnetic interference and lacking of energy due to the need to use induction from the line as power source [2, 4]. This paper proposes a new idea for the OLMS, to overcome the inaccuracy of the indirect methods and the problems of sensors installed on a high voltage line: the use of an infrared camera installed on the transmission tower and a passive target attached to the conductor.

The IR-camera will be installed pointing to the target, which must have high thermal conductivity to follow the conductor temperature along time. The target must also have a high emissivity in order to be visible for the camera and to increase the accuracy of the temperature measurement. Based on these conditions, the material and geometry of the target as well as the camera selection are discussed in this paper.

In section 2 the thermal behavior of the overhead lines and its relationship with the elongation of the conductor is explained. In section 3 the proposed design is described in detail and the criteria for the selection of a target and a camera are discussed. Moreover, some simulations and experimental results are shown in section 4 to illustrate the capabilities of the proposed system.

2 Decrease of clearance for high conductor temperatures

The conductor temperature increases proportional to the current square value but also depends on ambient factors as eq. 16.1 shows [2, 5]. The conductor heat losses are on the left side of this equation: convection q_c, which depends on the wind speed and direction; radiation q_r, whose value depends on the emissivity ϵ of the conductor; and the conductor heat storage, where C_p is the heat capacity of the conductor material and m the mass per unit length of the conductor.

The heat gains are on the right side of eq. 16.1: solar radiation q_s and the ohmic heat gain depending on the current flowing through the line and its temperature dependent resistance.

$$q_c + q_r + mC_p \frac{dT_{avg}}{dt} = q_s + I^2 R(T_{avg}) \tag{16.1}$$

The convection heat loss is the greatest term in eq. 16.1. This means that the wind plays an important role in the value of the conductor temperature. The wind direction and velocity normally changes along the line, i.e. a homogeneous conductor temperature cannot be expected. To illustrate this, the study made in [6] demonstrates how a punctual temperature measurement can deviate from the mean conductor temperature. This demonstration was done using punctual temperature sensors installed at several points of a line during a period of 12 hours. The result was a deviation of around ±40°C from the mean conductor temperature value [6]. This means that a single point temperature measurement cannot represent the temperature of the whole line.

On the other hand, as the conductor temperature increases so does its length. The relationship between them is linear and is shown in eq. 16.2 [7]. The constant α is the thermal expansion coefficient of the material and means how easy the conductor elongates for a change of 1K from the reference temperature $T_{c,ref}$. Greater values of α correspond to more elongation of the conductor from the same reference length L_{ref}.

$$L = L_{ref}(1 + \alpha(T_c - T_{c,ref})) \tag{16.2}$$

If the conductor length increases, the clearance from the line to ground decreases. The distance from the span (S, straight line between connectors) and the minimum point of the conductor curve is called the sag D. The sag plus the clearance to ground corresponds to the total height of the conductor connectors The relationship between sag and conductor temperature is shown in the eq. 16.3 [7] as an approximated version only valid for level spans (both poles are at the same height).

$$D \approx \sqrt{\frac{3S}{8}[L_{ref}(1 + \alpha(T_c - T_{c,ref})) - S]} \tag{16.3}$$

As an example, the sag of an ACSR Drake 403 mm^2 26/7 with 300m of span in the temperature range from −15°C to 80°C goes from 6.4 m to

9.1 m, that means a change of 2.7 m. The conductor length, on the other hand, increases 30 cm in the same temperature range. This increment in length could mean a dangerous situation for a transmission line and its surroundings, depending on the line case and weather conditions.

3 Concept description

This article proposes a new design for OLMS: Infrared imaging for a remotely detection and characterization of a target to determine the elongation of a transmission line in real time. Ice load and hot spots detection can also be derived from the same infrared image. Knowing the ambient temperature as well as the clearance to ground, ice loads can be estimated [8]. On the other hand, hot spots on the connections between conductor and insulator can also be detected using servomotors to change remotely its point of view: from the target to the line connections and vice versa. Hot spots are produced by damages on the conductor connectors. They mean loss of energy through heating and a fast detection of them avoids a break of the line [9]. With this system the TSOs can perform remotely manual checks of the line connections when considered appropriate, using the sensor unit already installed.

The camera is mounted on the transmission tower, therefore the need to power-off the line for installation is completely eliminated (normally a disadvantage of state-of-the-art systems with electrical sensors directly installed on the line). The passive target can be hanged on the overhead line using a hot stick, which reduces the system installation time. These advantages, the fact that there is just one sensor installed on the tower to measure clearance, ice loads and hot spots and the possibility to calculate the conductor temperature (if the current is known[1]), make this system a competitive solution compared to the state-of-the-art overhead line monitoring systems.

Clearance measurement can be done through the detection of the position of the target from the images produced by the IR camera. Since the target is following the conductor temperature, which is normally well above ambient temperature, the target can be seen by the IR-camera even at night without the need of extra-illumination. The

[1] A current sensor can be also installed in the tower if the TSO is not able to give a real-time current value.

advantage of using a target hanged on the line is the increment of the detection area from the conductor diameter (0.5 to 5 cm for Aluminum Conductor Steel Reinforced (ACSR)) to the target diameter, reducing the required resolution of the camera, i.e. reducing costs.

3.1 Target design

To design the target several parameters must be considered:

- High thermal conductivity: to maintain the target at a higher temperature than the surrounding ambient.
- High emissivity: To allow the detection of the target by the IR imaging device.
- Type of the line: Single conductor or a bundle.
- Low cost and weight.

The architecture proposed for the target is shown in figures 16.1 and 16.2. On the left side there is a target for the case of a single conductor and at the right side the quad-bundle[2]. In both cases they have a circular and symmetric form.

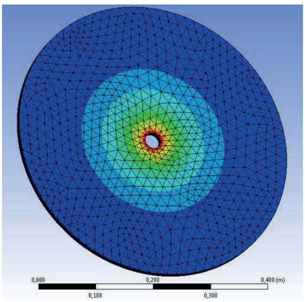

Figure 16.1: Target design for the single conductor case.

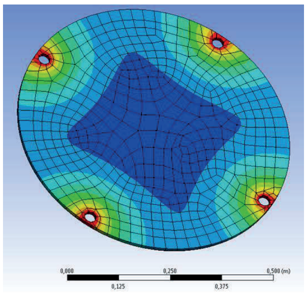

Figure 16.2: Target design for the quad-bundle case.

[2] In practice there are also bundles of two or three conductors, but for simplicity is only considered the four conductors bundle (quad-bundle).

The materials with highest thermal conductivity are the diamond and the copper. To keep the costs as low as possible, copper is the best option to construct the target (with a thermal conductivity of 400 W/m°C and a cost of around 4.2 Euro/kg). The disadvantage of it is its low emissivity (high reflectivity instead), i.e. for an infrared camera it will be invisible as long as it is not reflecting any IR-light coming from other objects. In this case a high emissivity coating like the offered by the company Aremco [10] can be used to cover it completely.

To determine the size of the quad-bundle target, the fact that normally the distance between conductors is 45 cm must be considered. In that case and supposing 3 cm for the conductor diameter, then the target diameter should be at least 68 cm. To reduce weight a meshed inner structure is proposed.

3.2 Camera selection

To select a appropriate camera the following criteria must be considered:

- Operating wavelength: Since normally the temperature of the conductor cannot exceed 80°C, the target temperature will be always below that value and then the imaging device can work in the long wavelength infrared range (LWIR, from 8 to 14 μm).
- Cooled or uncooled camera: Since the imaging in this system should work in the LWIR range, to reduce costs and energy consumption an uncooled camera is chosen.
- Number of pixels: The resolution of the clearance measurement depends on this parameter. The number of pixels should be enough to have at least a pixel for a change of sag of 2 cm (equivalent to approximately $\Delta T = 1°C$). To cover 3 m of change in clearance with this resolution, at least 150 pixels are needed in the vertical direction.
- Field of view (FOV): Since the target will be at a distance around 100 m to 150 m from the camera, the FOV must be narrow enough to have the target covering the most part of the image. For 150 m a FOV of 5°, for 100 m a FOV of 7° (considering a camera of 640x480 pixels and a resolution of 2cm per pixel).

4 Simulations and experiments

The thermal behavior of the target was simulated using the simulation software ANSYS. A conductor temperature was specified as the boundary condition of the target holes where the overhead line should be placed. The graphs in figures 16.3 and 16.4 show how the quad-bundle target follows the conductor temperature in the natural and forced convection cases[3], respectively. In both cases the ambient temperature was fixed at 22°C and the beginning temperature of the target is 50°C.

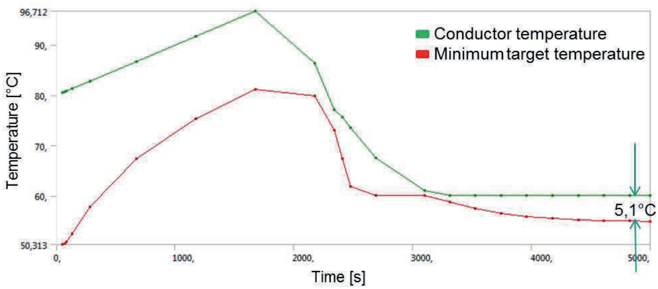

Figure 16.3: Natural convection of the quad-bundle target.

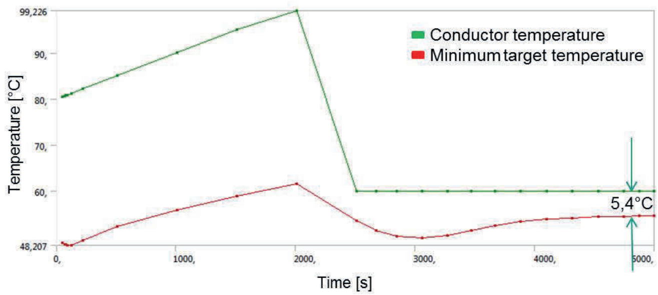

Figure 16.4: Forced convection of the quad-bundle target.

[3] Natural convection means almost no wind (less than 0.5 m/s) and forced convection corresponds to an effective wind velocity of 0.5 m/s or more [5].

In the natural convection case the target is able to follow better the conductor temperature as in the forced convection case. This is due to the fact that the target transfers more heat to the ambient because of forced convection. This result says that the camera will not be able to measure most of the time an accurate conductor temperature, because the target will not have a homogeneous temperature as long as the conductor temperature and the ambient conditions are changing. However, the goal of this system is not to measure temperature but to do a target recognition from an infrared image and hence to determine the clearance from the transmission line to ground. The achievement of this is possible as long as the mean target temperature is higher than the ambient temperature, which will happen providing that the conductor is under electrical load.

The automatic recognition of the target hanging from the conductor and its position measurement is made using image processing applied to the captured infrared data. As a general idea, the program should recognize the circular form of the target and return important parameters as the center of the circle and its radius. Using this information and knowing the camera parameters (FOV, number of pixels) as well as the distance camera to target, the distance from conductor to ground can be calculated.

A first version of the image processing program for this application was done making use of Matlab. Using this high level approach the capabilities of target detection algorithms can be tested. After that the algorithm can be programmed to be executed by the embedded system used in the overhead line monitoring system (a microcontroller, a DSP or a FPGA, for example).

The algorithm used to acquire the following results is based on the circular Hough transform [11]. Several images of a hot target (around 60°C) at different positions to the camera were captured with an infrared camera FLIR A655sc with a 24,6 mm lens (FOV: $25° \times 19°$) and 640×480 pixels.

From the captured images and knowing the radius of the target (7 cm) the distance from the camera to the target was calculated by the software and compared to the distance measured by hand. The manual measurement had a precision of 5 mm and the distance target to camera was between 1.17 m and 1.19 m at each image. The mean error obtained was 9.4 mm between calculated and measured distance,

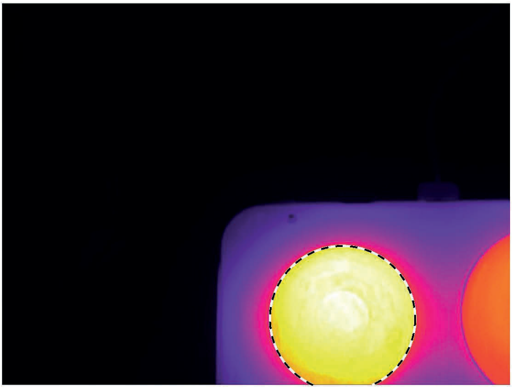

Figure 16.5: Target partially outside of the camera FOV and still recognized by the circular hough transform programmed in Matlab.

which corresponds to a 0.8 % of error. This result is considered interesting because this error includes a target partially outside of the camera FOV, which was still recognized by the software (see figure 16.5).

5 Summary

In this article a new approach for overhead line monitoring systems was presented: the use of an infrared camera to measure the clearance of the transmission line to ground, by detecting a target hanged on the conductor. With the results obtained was shown that the implementation and use of the proposed system is possible. The next step is the implementation of the idea on overhead lines, which implies new challenges as harsh weather conditions and the proximity to high voltage conductors.

References

1. M. Vollmer, "Infrared thermal imaging: fundamentals, research and applications," Weinheim, 2010.

2. D. Douglas, W. Chisholm *et al.*, "Real-time overhead transmission-line monitoring for dynamic rating," *IEEE Transactions on Power Delivery*, vol. 31, no. 3, pp. 921–927, Dec. 2016.
3. Tennet, "Netzausbau in Niederbayern: Stromversorgung zwischen Bayern und Österreich," Deutschland, Apr. 2015.
4. R. Stephen, "Real time monitoring," *Electra*, vol. 197, Aug. 2001.
5. Cigré, "Thermal behaviour of overhead conductors," Cigré, techreport 207, Aug. 2002.
6. G. Biedenbach, "Echtzeitmonitoring von Freileitungen: Leiterseiltemperatur zuverlässig ermitteln." *EW Magazin für die Energiewirtschaft*, vol. 7104, pp. 70–73, 2012.
7. Cigré, "Sag-tension calculation methods for overhead lines," Cigré, techreport 324, Apr. 2016.
8. G. Biedenbach, "Kapazitäten in Stromnetzen Optimal Ausschöpfen. Monitoring macht den Betrieb von Freileitungen sicherer." *EW Magazin für die Energiewirtschaft*, pp. 74–83, 2009.
9. J. Frate, D. Gagnon *et al.*, "Evaluation of overhead line and joint performance with high-definition thermography," in *Transmission and Distribution Construction, Operation and Live-Line Maintenance Proceedings*. IEEE, Oct. 2000.
10. Aremco, "High temperature high emissivity coatings," URL, 2016. [Online]. Available: http://www.aremco.com/high-emissivity-coatings/
11. B. Jähne, "Digitale Bildverarbeitung und Bildgewinnung," Berlin, Heidelberg, 2012. [Online]. Available: http://swbplus.bsz-bw.de/bsz377583960cov.htm