Requirements for High-Quality Thermal Inspection of the Transmission Lines

Igor Lukačević and Domagoj Lagator(✉)

HOPS d.d, Vukovarska Cesta 217, 31000 Osijek, Republic of Croatia
domagoj.lagator@hops.hr

Abstract. The paper deals with the basic characteristics of a thermographic camera important for the thermographic inspection of transmission lines. The specifics of the transmission line and the facts that can lead to incorrect measurement results are listed. Several thermographic images with a hand-held camera and a drone are shown. Each recording was analyzed, and possible shortcomings in the recording were listed. In conclusion, the minimum characteristics of hand-held thermographic cameras and thermographic cameras on drones are stated, as well as the recording conditions for correct thermographic inspection of transmission lines.

Keywords: Thermography · Transmission line · Thermal imaging camera · Drone

1 Introduction

In recent years, thermal imaging examinations have been an important method for diagnosing faults in high-voltage transmission lines. Transmission lines with nominal voltages of 110 kV, 220 kV and 400 kV are now regularly inspected with an IR camera every five years or as needed. The target inspection points are all junctions in transmission lines.

Thermal imaging inspections of transmission lines began to be regularly monitored ten years ago. Previously, these inspections were not performed as regular work because they were not prescribed as mandatory inspections in the internal rules of the electricity company. Such examinations were performed only in exceptional situations based on various indications. Due to increasing requirements for the availability of transmission lines, increasingly strict conditions for disconnecting certain sections of transmission lines and requirements to reduce maintenance costs, the deadlines for regular periodic maintenance (revision of transmission lines) have been extended. In order to maintain, or even increase, the reliability of the drive, regular periodic inspection of transmission lines with an IR camera was put into practice. The intended frequency of inspection is every five years. Inspections refer only to connection points on the transmission line, which are current bridges on tension poles, or repair connectors in places where the conductor has been changed or repaired.

Thermal imaging inspection of transmission lines has several specific features compared to inspections of other power plants:

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- the recording object (coupler) is relatively small and distant,
- the current load of transmission lines is difficult to influence,
- field nature of the work.

Due to the limited resolution of the camera sensor, the size of the object being recorded affects the accuracy and reliability of the results.

To avoid this problem, the cameraman must

- get as close as possible to the object,
- use a higher resolution camera,
- or use a lens with a narrower angle (telephoto lens).

To increase the possibility of spotting hot spots, the load on the transmission line should be as high as possible, which is difficult to influence on the transmission lines. Also, due to the development of modern technologies, inspections of power lines from the air have recently been carried out by unmanned aerial vehicles.

2 Technical Characteristic of IR Camera

2.1 Resolution

The resolution of digital cameras is one of their most important characteristics. The resolution of the camera sensor defines the number of pixels that convert the image into an electrical signal or a digital image. In the visible part of the spectrum we are talking about video resolution, and in the infrared part of the spectrum we are talking about thermal resolution. Given today's technological development in the field of digital cameras and video cameras, resolutions from ten to even one hundred megapixels are understood. In the field of IR devices, these values are much smaller. High-quality commercially available devices for civilian use generally have a resolution of up to 0.3 megapixels.

The resolution is most often expressed according to the size of the matrix in the number of pixels in the x and y directions. Today's IR cameras usually have a resolution of 160 × 120, 320 × 240, 640 × 480 and 640 × 512 pixels.

2.2 Lens

The role of the thermal camera lens is the same as the role of the lens of an ordinary camera, i.e. it focuses thermal radiation on the matrix of thermal sensors. However, thermal imaging camera lenses are made of germanium because ordinary glass is not permeable to infrared radiation. For this reason, the price of thermal lenses is several times higher than that of visible light lenses (Fig. 1).

The basic characteristic of the lens is the angle of view (AOV) and field of view (FOV). The usual viewing angle of a thermal camera is 24°. However, more complex and better quality cameras allow changing lenses. Lenses ranging from 7° (telephoto lenses) to 45° (wide-angle lenses) can thus be used.

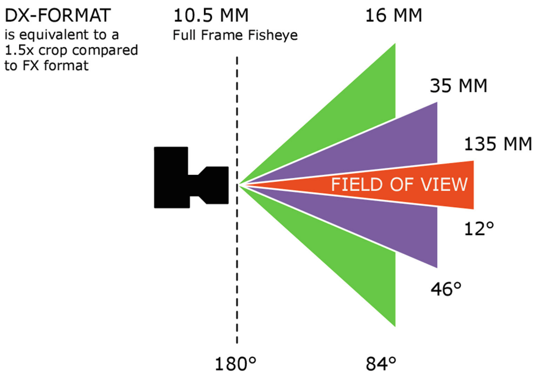

Fig. 1. Illustration of camera resolution and field of view

From the resolution of the camera and the field of view of the lens comes the most important characteristic of the camera, which is the field of view of one pixel (IFOV—Instantaneous field of view). Let's assume that the thermal camera has a resolution of 640×480 pixels and has a lens with an angle of 24°.

The IFOV parameter is calculated [1]:

$$\begin{aligned} 24^{\circ}/640 \text{ pix} &= 0.0375^{\circ} \\ &= 0.00065 \ \text{ rad} \\ &= 0.65 \ \text{ mrad} \end{aligned}$$

So one pixel covers an angle of 0.65 mrad, which means that at a distance of one meter it covers an area of 0.65 mm.

For ideal camera optics, it would be sufficient if the observed object was larger than the area covered by one pixel for the temperature reading to be accurate (Fig. 2a). However, it is not certain that the pixel will always be centered on the object (Fig. 2b). In this case, the measured temperature will be the average temperature of the object and the ambient temperature. Measurement error is certainly present if the observed object is smaller than the pixel size (Fig. 2c) [1].

Given that the optics of the lens are not perfect, part of the thermal radiation is scattered by passing through the lens. In this way, a diffused image is created around the pixel and all the radiation does not fall on it. Therefore, a larger number of pixels per object is required to avoid measurement error. The area covered by a pixel for correct measurement is denoted by MFOV (Measurement Field of View or True IFOV) (Fig. 3) [1].

For modern cameras with good optics and taking into account the above, the size of the observed object should not be smaller than the area covered by 3×3 pixels.

2.3 Other Characteristics

In addition to the above-mentioned characteristics, each camera has a whole series of characteristics related to recording itself, ergonomics, functionality, specific purpose, robustness, software characteristics, etc. We will single out just a few:

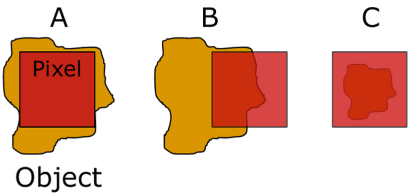

Fig. 2. Illustration of the relationship between pixels and the observed object [1]

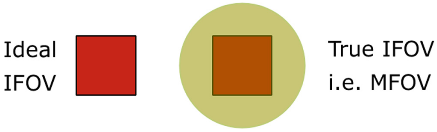

Fig. 3. Scattering of radiation around an ideal pixel [1]

Thermal sensitivity or Noise Equivalent Temperature Difference (NETD) describes the smallest temperature difference you can see with the camera. Typical values are 100 mK for worse models to 30 mK for better models. Figure 4 shows the difference in thermal images for two different thermal sensitivities.

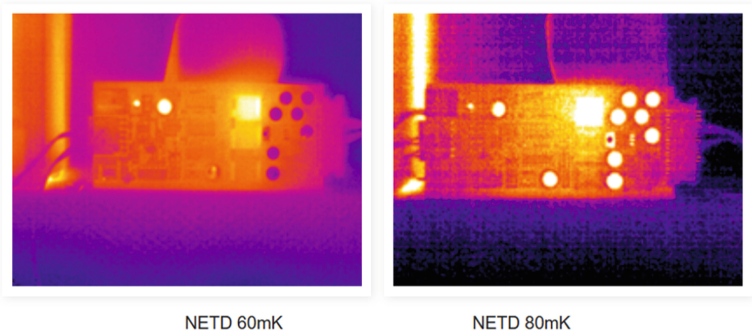

Fig. 4. Thermal images made by cameras with different thermal sensitivities

Zoom—IR cameras, as a rule, do not have the possibility of optical zoom, but the image enlargement is performed by software. This way of enlarging the image cannot improve and increase the accuracy of the measurement, but it can help in noticing details and more precise focus/sharpening of the image [2].

Focus—In lower class cameras, the focus or sharpening of the image is achieved automatically. With higher class cameras, focus can be done automatically or manually. When using a telephoto lens (with a smaller viewing angle) and recording smaller and more distant objects, manual focus adjustment is necessary [2].

Refresh rate—The refresh rate of the thermal image is important for recording moving objects and when you want to make a thermal video. Refresh rates range from 7 Hz to 30 Hz [2].

Software image enhancement—By applying various methods of interpolation and digital image processing, image resolution can be increased (Fig. 5). The correctness of the application of these methods depends on the assumed physical model. Since heat propagation is a spatially continuous phenomenon without sudden discontinuities, the surface interpolation of the measured values makes sense (as in the example in Fig. 5). However, when imaging a spatially isolated object such as an electrical conductor or coupling in air, there is a large discontinuity in the temperature of the observed object and the background. Namely, in this case the background is the sky with an extremely low radiation temperature, which in clear weather is around −70 °C (−46 °C in Fig. 6). In this case, applying any interpolation can lead to incorrect temperature readings [3].

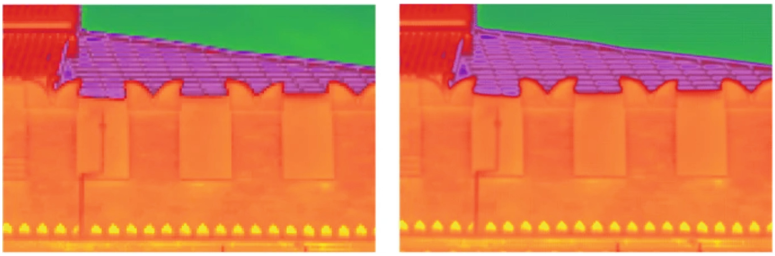

Fig. 5. Software enhancement of thermal image resolution

3 Specifications of Thermal Vision Inspection of Transmission Lines

Thermal imaging inspection of transmission lines is performed in order to identify bad connection points where excessive heating of conductors and connectors occurs. Therefore, the connectors of the phase conductors are primarily inspected. These couplings can be of compression or screw type and are located primarily on tension columns. In addition to the tension poles, teaching and repair couplings can be located anywhere in the transmission line route.

Let's list some basic peculiarities of recording these objects:

- The size of the observed object is relatively small considering the distance. The diameters of the phase conductors of transmission lines range from 16 to 31 mm.
- The distance of the measuring device (camera) from the object is relatively large. For practical reasons (high altitude, accessibility of the route) and safety (high voltages), the measurement is made from a distance that is rarely less than 20–30 m. In recent years, when recording from drones, this value is much smaller. The average distance when recording from a drone is about 3–10 m.

- The background of the object is extremely low temperature (atmospheric radiation temperature, depending on the weather conditions, drops to—70 °C).
- Manipulations with the switching state of the network can hardly increase the load on the transmission line in order to facilitate the detection of a hot spot. As a rule, power lines are under low load at the time of recording.

According to Sect. 2.2. Let's calculate the maximum angle of the camera lens.

- assume the value of MFOV is 3 pixels and the thickness of the conductor is 20 mm
- it follows that 1 pixel must cover an area of 20 mm/3 = 6667 mm

At a distance of 30 m from the object, it follows the:

- IFOV = 0.006667 m/30 m = 0.00022 mrad.

For a camera with a resolution of 640 × 480 pixels, we calculate the required viewing angle of the lens

- 0.00022 mrad * 640 pix * 180°/π = 8149°. (standard lenses on the market have an angle of 7°).

Figure 6 shows a correct thermal image of tension clamps on a 110 kV transmission line made with a camera with a resolution of 640 × 480 pix and a 7° lens from a distance of approx. 25 m. When using a 7° lens, attention must be paid to sharpening the image. The maximum sharpness of the image is achieved by manually adjusting the focus of the lens with the mandatory use of a geodesic or photographic tripod. Figure 7 shows a defective thermal imaging image due to poor image focus, regardless of the fact that the correct equipment was used (camera 640 × 480 pix, lens 7°).

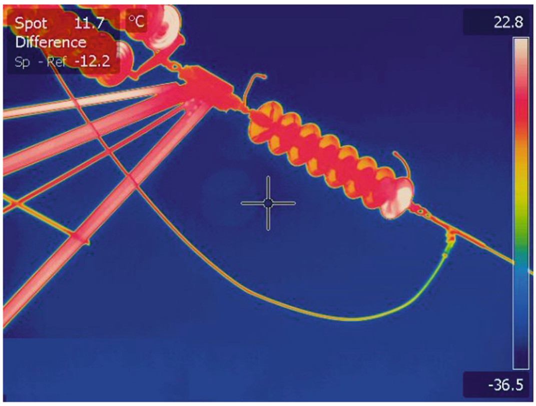

Fig. 6. Thermal image of tension clamps on a 110 kV transmission line made with a camera with a resolution of 640 × 480 pix and a 7° lens from a distance of 25 m

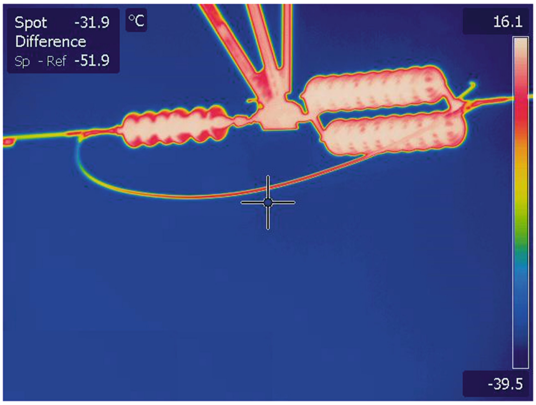

Fig. 7. Defective shot due to poor image focus

Due to the development of technology recently, unmanned aerial vehicles are also used for inspections of power lines, including thermal imaging inspections. The advantage of this kind of inspection is that the object can be approached at a shorter distance, regardless of the accessibility of the route. The disadvantage is that the payload of drones is limited and large cameras cannot be used. Regardless, technology has managed to assemble cameras of compact dimensions for unmanned aerial vehicles that can provide the same quality image as much more expensive cameras for recording from the ground.

An example is a camera with a resolution of 640 × 512 pix and a wide-angle lens of 40.6°. Let's calculate to what distance from the 20 mm diameter guide the unmanned aerial vehicle with such a camera must approach for a correct thermal image.

$$\text{IFOV} = 40.6^{\circ}/640\ \text{pix} * \pi/180 = 0.00111\ \ \text{mrad}$$

With the assumed MFOV of 3 and a conductor thickness of 20 mm, the maximum distance d is

$$\text{d} = 0.020\ \ \text{m}/(0.00111\ \text{mrad} * 3) = 6.01\ \ \text{m}$$

Approaching such small distances requires great attention and experience of the pilot, as well as the resistance of the unmanned aerial vehicle's equipment to electromagnetic influences. Also, it is difficult for the pilot to judge the actual distance of the aircraft from the object.

Figure 8 shows a thermal image of a 110 kV transmission line made by an unmanned aerial vehicle with a 640 × 512 pix camera and a 40.6° lens. The picture was taken from a distance of about 3 m. The advantage of shooting with an unmanned aerial vehicle is an easy check whether it is really a warm place or a reflection. Shooting with a camera requires a lot of moving and checking that takes a long time. Shooting with an unmanned aerial vehicle enables a quick change of the shooting angle and repeating the shot of the object.

Subsequently, a power line team was sent to the field to determine if it was really a warm place. The transmission line was disconnected and the recorded current bridge was dismantled. After disassembly, it was evident that the recording was correct and that the warm spot was correctly detected.

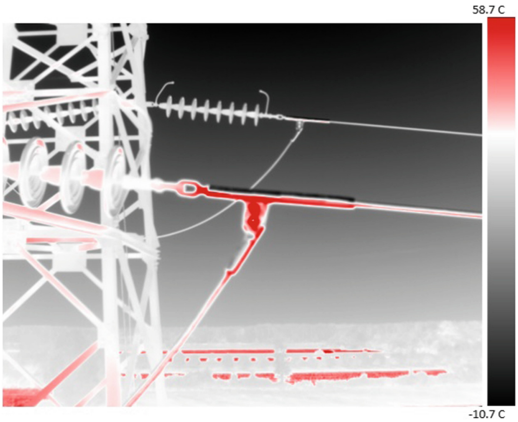

Fig. 8. Thermal image of a 110 kV transmission line made by an unmanned aerial vehicle with a 640 × 512 camera and a 40.6° lens

The next few pictures show thermal imaging images made in an incorrect way and perhaps with wrong conclusions. Figure 9 shows a thermal image of a 110 kV transmission line in the coastal area. The image is of low resolution and it is difficult to draw a correct conclusion from it. The temperature reading of the connectors shows a temperature difference of about 20 °C. Given that the recording was made in March in the coastal area, it is not realistic that the conductor temperatures are below 0 °C, especially if it is compared to the temperature of the structure. The low conductor temperature reading is the result of averaging the actual temperature with the extremely low sky temperature.

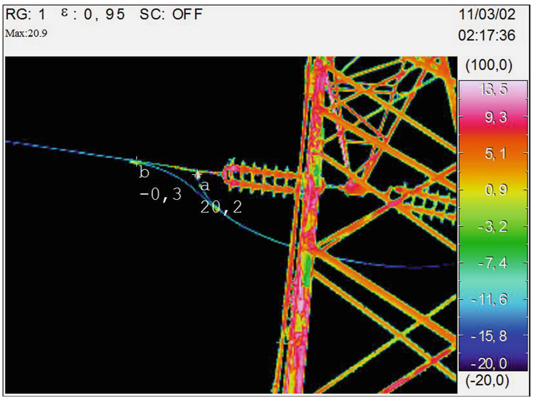

Fig. 9. Thermal image of 110 kV transmission line in the coastal area made with a 320 × 240 pix. camera

Figure 10 shows a thermal image of a column where potentially bad connection points can be seen. Due to the chosen small temperature range of the image (0.3 °C to 6.3 °C), the observed points appear extremely warm, but the real difference compared to the ambient temperature is approx. 4 °C. It is also unlikely that all four clamps shown are faulty. Namely, there is no electrical connection at all on the clamps shown, i.e. conductor breaks.

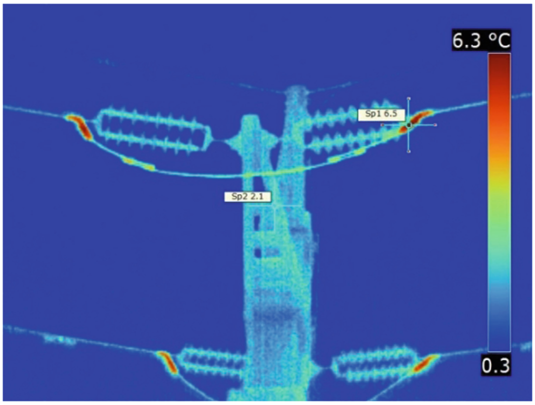

Fig. 10. Thermal imaging image of a 110 kV transmission line pole with insufficient resolution

Figure 11 shows a shot of a 400 kV transmission line with a good resolution camera (640 × 480 pix) but with a wide angle lens (24°) and from a long distance. Nothing can be concluded from this picture about the condition of the connection points on the transmission line.

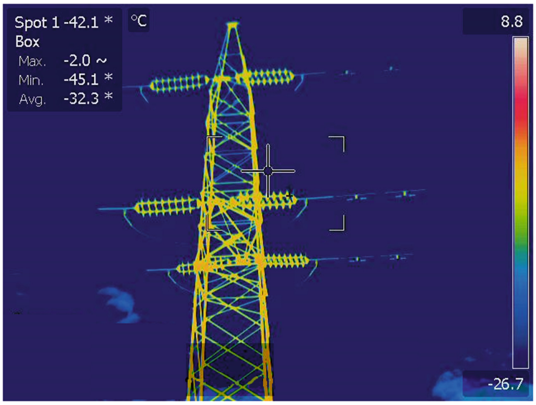

Fig. 11. Thermal image of a 400 kV transmission line with a camera of good resolution (640 × 480 pix), but with a lens with a wide angle (24°) and from a long distance

4 Comparison of the Specifications of a Handheld Camera and a Drone Camera

Recently, there has been a lot of discussion about which camera is better to use in work and which gives better measurement results. Like everything, this depends on the situation, but in general it can be said that both cameras give excellent results when used within their operating parameters and when all the rules of thermal imaging are followed.

In transmission system operator, we have been using the IR camera FLIR P660 in combination with a narrow-angle 7° lens for thermal imaging examinations for a long time. Two years ago, we also started using an IR camera carried by an unmanned aerial vehicle. It is a DJI H20T camera.

A hand-held camera has its advantages when recording power plants, because drone flights are not possible in these areas. Likewise, these are extremely accessible spaces and it is easy to move the camera and take quality shots.

Hand-held cameras also have their advantages when recording isolated transmission line poles that are extremely accessible, that is, those poles that can be reached by vehicle. The reason for this is that the preparation of the drones, as well as the preparation after the flight, still requires a certain amount of time.

If the pole is on inaccessible terrain, or if it is in the middle of some culture, that is, if the pole is in a fenced area, or if we have several tension poles in a row, then the drone camera wins.

For example, 6 poles of a 400 kV two-system transmission line were recorded from one takeoff with an unmanned aerial vehicle (a total of 36 points for checking). This would require a minimum of 12 moves using a handheld camera to capture everything and it would be necessary to reach the base of all 6 towers (Table 1).

Using the calculation from Sect. 3, in Table 2 we will give the maximum distances from which it is possible to obtain a high-quality recording when recording conductors and equipment on portable transmission lines.

When filming with a hand-held camera, we can say that as a rule we always shoot from a limited distance because it is often difficult to approach each column to its base.

When filming with a hand-held camera, we can say that as a rule we always shoot from the limit distance because it is often difficult to approach each pillar to its base. When filming with an unmanned aerial vehicle, we are always below the limit distance, it is rarely filmed from a distance that is close to the limit. Another advantage of an unmanned aerial vehicle is that it is possible to see the exact distance of the object from the aerial vehicle at any time, while this is not possible when recording with a camera unless some distance measurement equipment is additionally worn.

5 Conclusion

Based on the above, it can be concluded that for a reliable thermal imaging inspection of transmission lines by recording from the ground, a camera with a resolution of at least 640×480 pixels and a lens with an angle of 7° should be used, provided that the location of the recording is as close as possible to the object. Likewise, aerial photography is also

Table 1. Comparison of the two types of cameras used in the event thermal imaging of transmission lines in the transmission system

	Flir P660 + 7° lens	DJI H20T
Resolution	640 × 480 pix	640 × 512 pix
Lens	24° (serial), 7° (optional)	40.6°
Temperature sensitivity	0.045 mK	0.050 mK
Temperature range	−40 °C do 500 °C	−40 °C do 550 °C
Zoom	digital 8x	digital 8x
Refresh rate	30 Hz	30 Hz
RGB camera	built-in 3.2 Mpix camera does not work when using the 7° lens	built-in camera 20 Mpix, 23x optical zoom
GPS	yes	yes
Post-processing of the image	yes	yes
Maximum distance when recording conductors with a diameter of 20 mm	35 m	6 m
IP protection	None	IP44

Table 2. Comparison of the maximum distances for creating a quality thermal image.

Conductor type (ACSR) (mm^2)	Flir P660 + 7° lens (m)	DJI H20T (m)
490/65	53	9
360/57	46	8
240/40	38	6.5
150/25	30	5

possible. All cameras with a resolution higher than 640 × 480 are good, as well as any camera with a shooting angle of less than 40.6°.

In addition to these specifics of transmission line imaging, other conditions for high-quality thermal imaging must also be considered. The basic requirement is a well-trained videographer with experience in interpreting thermal imaging images. It is also necessary to know the technical characteristics of the recorded object, types of materials and emission factors, etc., but this is not the subject of this paper.

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