Using Infrared (IR) Thermography to Improve Electrical Preventive Maintenance Programs

White Paper 268

Revision 0

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Executive summary

IR thermography can be used both at startup and during on-going operations to locate potentially dangerous problems quickly allowing for a controlled shutdown before unplanned interruptions in service occur. It can prevent premature failure and extend equipment life, and reduce costly outages and downtime. However, if done improperly, these benefits may not be realized. This white paper explains what IR thermography is, provides best practices to follow while performing an IR scan, and highlights some important factors for interpreting the resulting thermogram.

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Introduction

Infrared (IR) thermography is a method used to identify potential problem areas by detecting "hot-spots" in electrical systems. The underlying principle for this method is that most components tend to show an increase in temperature while malfunctioning. For instance, this rise in temperature could be caused by loose connections, defective or deteriorated equipment, short circuits, overloads, load imbalances, and even incorrect installations to name a few. IR thermography allows one to observe the heat patterns in a system which can be used to help identify the location of a potential problem area; this can be analyzed and fixed, if needed, before the equipment fails and causes further damage.

IR thermography is most commonly used during initial start-up (commissioning) for detecting abnormalities, and in preventative maintenance programs as described in NFPA 70B[1]. When using this process during initial startup, the goal is to identify "hot-spots" for further evaluation whereas with preventative maintenance programs, it is used to compile a history of collected data that can be used to identify changes and/or trends in the data. Such focus on data trends as opposed to specific temperatures is common in preventative maintenance programs and is often referred to as trending.

The process of IR thermography involves testing by using a camera-like device called a thermal imager or a thermograph as shown in **Figure 1**. This device is used to scan a large area at a time in order to capture natural infrared emissions from the equipment and convert them into a visual thermal image, called a thermogram. This thermal image is then used to analyze the equipment. IR thermography is thus an example of non-destructive or non-invasive testing.

Figure 1
An infrared camera / thermal imager

In colored thermograms, white and red colors are usually used to depict hotter areas, and black and blue colors are used to depict cooler ones. **Figure 2**[2] shows some examples of thermograms showing malfunctioning equipment. These examples illustrate the differences between the hot and cool areas.

There are several benefits to IR thermography like locating potentially dangerous problems quickly and performing a controlled shutdown before unplanned interruptions in service occur, preventing premature failure and extending equipment life, and reducing costly outages and downtime. Both the image acquisition and the image analysis phases need to be performed with great skill in order to reap the benefits of this crucial preventative maintenance tool. The users of IR thermography

[1] NFPA 70B: Recommended practice for electrical equipment maintenance. National Fire Protection Association, 2013.

[2] Electrical distribution systems. IRINFO.ORG, a division of T/IR Systems LLC. (http://www.irinfo.org/application_electrical_distribution.html

should therefore hire the right expertise, or, spend the resources in developing the same in-house. This would greatly reduce the chances of missing hazardous failure spots, and equally important, reduce the number of false alarms.

Figure 2A
Improperly closed air switch

Figure 2B
Load imbalance on bus duct

Figure 2C
Loose or deteriorated fuse clips

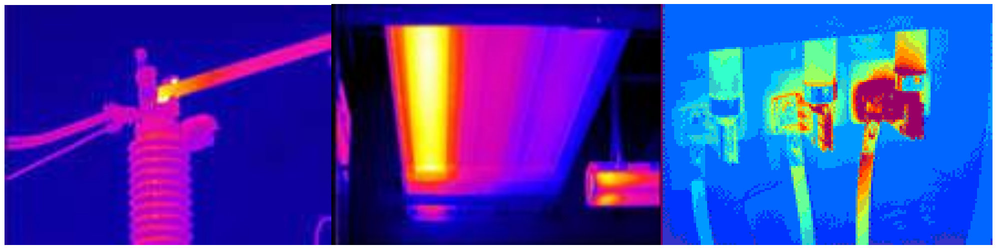

Figure 2A Figure 2B Figure 2C

This white paper explains what IR thermography is, provides best practices to follow while performing an IR scan, and highlights some important factors for interpreting the resulting thermogram. The main goal of this white paper is to help identify real concerns in the system while trying to alleviate concerns that arise due to inaccurate data collection or due to misinterpretation of the images.

Data collection process

The National Fire Protection Association (NFPA) has a standard, NFPA 70B, that details recommended maintenance in electrical, electronic, and communication systems and equipment such as those used in industrial plants, institutional and commercial buildings, and large multi-family residential complexes[3]. Through these maintenance recommendations, this standard intends to help prevent equipment failures and worker injuries. It provides guidelines for an effective Electrical Preventive Maintenance (EPM) program and explains why this is essential to protect lives and property.

One of the testing methods that is recommended for electrical equipment maintenance by NFPA 70B is IR inspection. In what follows, we list important points which can be thought of as "best practices" while conducting an IR thermography scan.

- Make sure the system is operating at loads no less than 40% of the rated load. In fact, NFPA 70B states that IR scans should be performed during periods of maximum possible loading. Recall that heat output from the equipment is proportional to the square of the current. Thus, running equipment at loads closer to full load aids in easier detection of defects[4].
- IR images should not be captured through generic glass doors or windows. Some equipment have special windows to shoot IR images. In cases where IR windows are not provided, when safety procedures allow, electrical enclosures will need to be opened for inspection[5]. This, however, increases the risk of triggering an arc flash and NFPA 70E should be referred to for appropriate procedures, training, and personal protective equipment (PPE).
- Wind and air-currents due to natural environmental sources should definitely be considered and accounted for as they might cool hot-spots very quickly to levels below the threshold of detection. Ventilators and air-conditioners used for climate-control can have a similar effect too. In conditions where this may

[3] NFPA 70B: Recommended practice for electrical equipment maintenance. National Fire Protection Association, 2013.

[4] Electrical distribution systems. IRINFO.ORG, a division of T/IR Systems LLC. http://www.irinfo.org/application_electrical_distribution.html

[5] Applying infrared thermography to predictive maintenance. Fluke Corporation white paper. 3/2010 2435559C A-US-N http://support.fluke.com/find-sales/download/asset/2435559_6003_ENG_B_w.pdf

be likely, enclosures should be opened only after the camera settings are set and the camera is in focus to gather the most accurate temperature readings[6]. Factors such as these might cause potential defects to go undetected by reducing the temperature difference between hot and cold areas.

- Ambient temperatures can have a significant influence on the readings captured as well. If the surrounding temperature is too hot it might mask the hot-spot in the thermal image. On the other hand, low ambient temperatures might cool down hot-spots quickly. In both these cases, the defect will appear like a warm area. Thus, ambient temperatures should be recorded and accounted for while analyzing the thermogram.
- Emissivity of a material is defined as the relative ability of its surface to emit energy by radiation as compared with a black-body[7]. The emissivity setting on a thermal imager needs special attention before making readings.

There are two types of inspections that can be performed – quantitative and qualitative. For quantitative inspections, it is important to know the emissivity of each object being analyzed in order to obtain accurate temperature values. Special attention should be given to highly reflective surfaces and unpainted metals as reflections from such surfaces will interfere with accurate temperature measurements[8]. Refer to the section on interpreting images for tips on how this issue can be overcome in certain cases. However, quantitative analysis may not always be necessary[9]. It is more common to perform so called qualitative analysis for routine inspections. In these types of inspections, the goal is to observe trends in temperature for the same object over time, or, for same parts in similar equipment. Since the evaluations are done on a relative basis, this allows one to set emissivity to 1.0 in the thermal imager. As mentioned earlier, this is often referred to as "trending" data. Due to the large number of variables involved in obtaining accurate temperature values as discussed throughout this paper, trending is often the preferred method of using IR thermography, when practical.

- The thermal camera angle and location should be considered carefully. They should be varied to see if any apparent hot-spots disappear. If the hot-spot disappears when the camera angle is slightly altered, then it clearly shows that this apparent hot-spot was caused by reflection. Direct sunlight and other light sources might be reflecting off metal surfaces and might affect the image. These reflections could interfere with the image during and sometimes even after the exposure has ended.
- A thermal image as well as a visual image of the equipment should be captured in order to be able to easily identify the components at a later stage. It is important to capture both of these from the same angle and distance to avoid confusion. Additionally, the images should be such that enough surrounding area is also captured to easily locate the equipment in the future[10].

For example, consider the images shown in **Figure 3**. The image on the left shows the thermal image for a particular set of conductors, and the image on the right is a

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[6] Denio, H. Interpreting the images: Data errors in thermography – electrical & roofs. http://www.irinfo.org/articles/06_01_2007_Denio.pdf

[7] Siegel, R., and Howell, J. Thermal radiation heat transfer. Taylor & Francis, 2002

[8] Denio, H. Interpreting the images: Data errors in thermography – electrical & roofs. http://www.irinfo.org/articles/06_01_2007_Denio.pdf

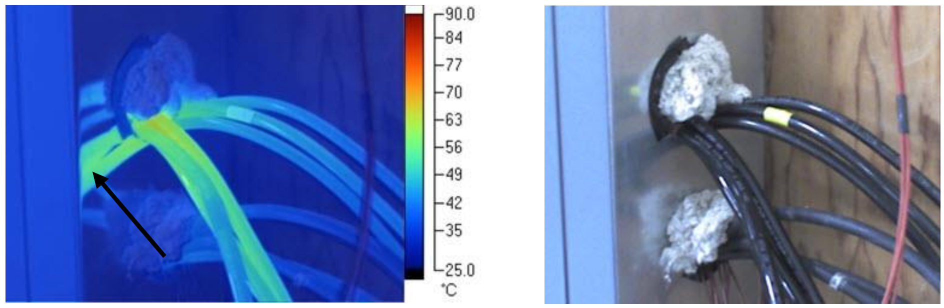
[9] Clausing, L.T. Emissivity: Understand the difference between apparent, actual IR temps. http://www.reliableplant.com/Articles/Print/14134

[10] Denio, H. Interpreting the images: Data errors in thermography – electrical & roofs. http://www.irinfo.org/articles/06_01_2007_Denio.pdf

visual picture of the equipment. The arrow in the thermal image points to what appear to be cables. However, when the visual image is analyzed, it is clear that this is merely a reflection of the actual cables. Thus, only analyzing a thermal image might sometimes cause misleading results.

Figure 3

Example showing the importance of capturing a thermal as well as a visual image to avoid any confusion about the equipment during analysis of the thermal image.



Thermal image for a set of cables   Corresponding visual image

- In some rare cases, cold areas in the image might actually be the faulty parts. For example, a blown fuse will not pass any current through and will appear colder than the other components. Care should be taken to understand the working of equipment carefully and make notes about the equipment during image collection that will later help identify what the heat-related failure signs might be for those pieces of equipment.
- Maintain records of numerical temperatures as well as thermal images that will help in qualitative analysis used to evaluate trends in heating patterns of the same equipment over time. The thermal imager settings at which these particular thermal images were captured should be recorded as well in order to be able to recreate them later to observe trends accurately.
- Another piece of information that would be valuable is the measured current in each phase at the time of the scans. This will help determine if the loading is consistent and if the phases are balanced.

Interpreting images

Accurate interpretation of a thermal image is as important as the data collection process itself. For instance, every image will have a hottest spot, but that does not mean that the temperature at this particular equipment is higher than its threshold or that the particular equipment is malfunctioning. For example, a hot-spot might just be an indicator that this equipment is hotter than the rest of the system around it. In this section of the paper we will review some key points to remember while interpreting hot-spots before determining equipment is defective.

Temperature conversion

The temperature scale on the thermal imager might be set to °F while the standards list temperature limits in °C. For instance, a common busbar joint allowable temperature rise per UL891 is 65°C but when converted to the Fahrenheit scale it is 149°F. This difference in temperature scales might lead to false alarms if not considered correctly.

If this is the case, either the settings on the camera should be set to the same scale as the temperature limits being compared, or accurate temperature conversion from °F to °C (or vice versa) should be performed before comparing measured values with listed permissible limits. Recall that the conversion from °F to °C is given as

$$^{\circ}C = (^{\circ}F - 32) \times \frac{5}{9}$$

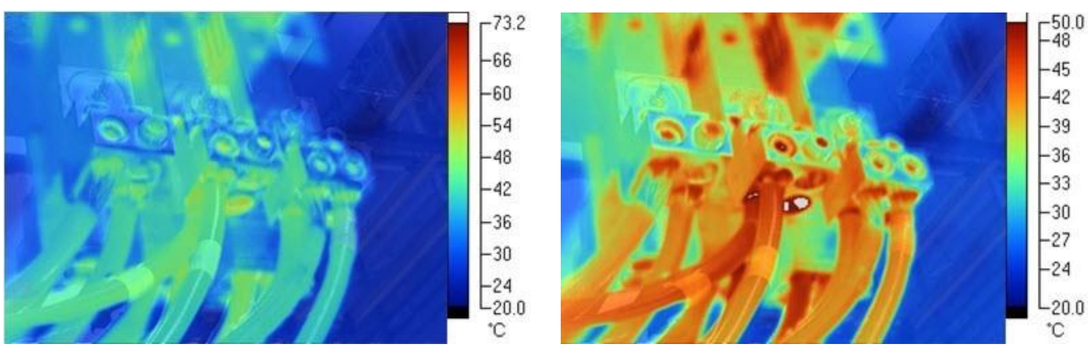
Color scale setting

Another important camera feature that should be carefully reviewed is the span and level that the color scale is set to in the displayed thermal image. Different cameras have different options for setting the color scale. Refer to your camera instructions for setting color scale. If these are set incorrectly, they might result in some equipment appearing as hot-spots (red or white colors) even though their temperatures might be well within permissible limits. Without this feature, the camera will detect the maximum and minimum temperatures in the entire area being scanned (including the environment) and display all the temperatures in that range. This makes it difficult to gauge if the hot-spots in the thermal image actually correspond to a defect.

We recommend you set the color scale such that the threshold temperature is displayed, for instance, by color red. Then, every region whose temperature is below this threshold will appear as "cooler" colors and will not be of concern. This will help to easily narrow down the problem spots. Consider **Figure 4** for example. The image on the left has the color scale set at 73.2°C as the upper limit. In looking at this picture, all objects appear to be below the upper limit. However, when the color scale is changed to 50°C, as seen in the right image, there are many objects that "appear" to be hot.

In order to decide which image is correct, the threshold temperature of concern should be decided. In this case, if the cable connections are being inspected and have a temperature rise limit of 50°C, and the ambient temperature is 23.3°C, then the absolute temperature limit is 73.3°C (50°C + 23.3°C). Therefore, the image on the left was taken with the correct color scale. Note that any equipment above the upper limit of the color scale will appear white.

Figure 4
Thermal images of the same equipment with the camera being set to different color scales.



Color scale set to 73.2°C

Color scale set to 50°C

However, this does not mean that every component above the threshold color is of concern. This is especially true with steel supports, required for the basic structure and design of electrical equipment, that are close to energized busbars. Due to the close proximity of steel support members to live busbars, they can get hot and often exceed many of the temperature limitations of other components around them. This situation often results in the steel member being the hottest spot in the equipment and is displayed this way in the infrared scan. For example, consider the threshold being set to 85°C which may be the threshold of a specific plated busbar joint (65°C rise + 20°C ambient). When the image is taken, a metal support bracket may be in the image and be displayed by a temperature color, say white, indicating temperatures in excess of 85°C. This situation often raises concerns. However, it is important to note that metal support brackets located near an energized busbar can display higher temperatures and still be perfectly acceptable as long as other considerations are taken into account. Some of these considerations include, for instance, nearby busbars being within limits, temperature limits of other support members not being exceeded, temperature of paint being within limits, and insulating materials not getting damaged. Thus, some components may not really be problem spots even though they are at temperatures higher than the threshold setting.

When there are several different temperature limitations given in the standards for similar equipment, the color scale should be set to the lowest of the listed temperatures for a conservative reading. In some cases when the exact class of the equipment cannot be determined, the lowest temperature referenced in the standards for that equipment group should be used.

As mentioned in the data collection process section, if data is being used for trending, then the color scale should be set the exact same way each time for a more accurate comparison.

Emissivity setting

For the purposes of thermography, emitted energy from any object is what is most important because it is the indicator of the object's temperature[11].

A highly reflective object is known to be less emissive, and vice versa. Refer to the Appendix for further details on this relation between reflectivity and emissivity. Since a highly reflective object is less emissive it might cause a defect to go undetected during the thermography process. However, if there is a hotter object in the vicinity, then it will reflect heat off of that object and appear hotter than it actually is. Thus, understanding the material properties of the equipment under consideration is very important before drawing any conclusions based on a thermal image[12].

Since emitted energy is an indicator of the object's temperature, we would prefer equipment to be dull and less reflective, and instead have a high emissivity value in order to get a more accurate reading of its temperature. Unfortunately, the emissivity of most transmission and distribution equipment is quite low[13]. Thus, detecting the temperature of an object by just measuring its total infrared radiation will most probably result in errors in the data. In order to get more accurate temperature readings for quantitative analysis, the object's emissivity must be known. For instance, the emissivity value for a plated busbar may be different than that for an un-plated bus bar. So we can see that when quantitative analysis of equipment is being performed, the emissivity setting on the imager can play a significant role. Of course, even when the emissivity values are known, obtaining accurate temperature readings can often be difficult. This is because of the various factors discussed throughout this paper, including setting and using the camera correctly.

If hot-spots are noticed in a thermogram, then it should be carefully reviewed to make sure that it was not reflections that were hindering the imager from getting an accurate output. If this was indeed the case, there are two main ways to overcome this issue:

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[11] Epperly, R. A., Heberlein, E., and Lowry G. E. A tool for reliability and safety: predict and prevent equipment failures with thermography. IEEE Petroleum and Chemical Industry Conference, 1997: 59-68.

[12] Clausing, L.T. Emissivity: Understand the difference between apparent, actual IR temps. http://www.reliableplant.com/Articles/Print/14134

[13] Snell, J. R., and Renowden, J. Improving the results of thermographic inspections of electrical transmission and distribution lines. AeroSense, International Society for Optics and Photonics, 2000: 115-126.

A. Most modern thermal imagers have a compensation setting that mathematically corrects for this issue within the signal processor of the thermal imager. The operator can quickly and easily set this setting if the emissivity values for the equipment under consideration are known. Usually, a list of emissivity values for common materials is provided in the thermal imager manual. This should only be used as a rough guide because emissivity varies by surface condition, viewing angle, temperature and even by spectral wavelength. Sometimes even small errors in emissivity values for shiny metals can cause large errors in the temperature readings.

B. When the emissivity setting is unknown, an easy and common way to significantly reduce errors in measurement due to highly reflective surfaces is to paint a flat black spot using "high temperature" paint, or to use "high temperature" flat black electrical tape that is not shiny (called calibration tape) on the equipment where temperature is to be scanned. This effort to standardize emissivity is usually done while the equipment is de-energized. Usually, a 1" to 2" diameter circle of paint or piece of tape is used. Both black electrical tape and a flat black spot of paint have high emissivity of approximately 0.96 (usually close to 1.0). This helps elevate the target to higher emissivity levels and thus get a more accurate reading. This is shown in **Figure 5** below. The black electrical tape placed as an "X" on the busbar helps obtain a more accurate reading of the busbar temperature. Note that the tape shows the busbar temperature to be about 60°C (red) which is the actual temperature, whereas the surface without the tape is about 32°C (blue).

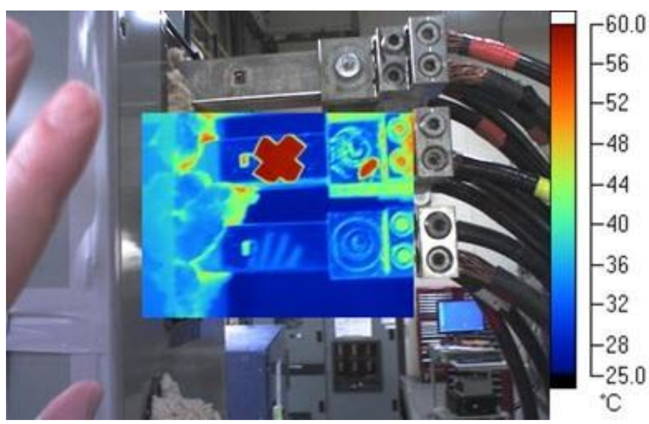


Figure 5
Thermal image of a busbar overlaid on its visual image to show the effect of the cross-marked black tape, and the reflection of a hand due to the shiny surface of the busbar.

However, this is not always practical at very high temperatures. At these extremely high temperatures, errors due to unknown emissivity of materials can be avoided by using imagers that use narrow wavelength bands at shorter wavelengths.

- Reflections: As discussed above, highly reflective surfaces hinder accurate temperature readings. Any heat source in the area, including the operator's own thermal radiation, could have caused confounding reflections resulting in a properly functioning area appearing falsely as a hotspot. For instance, **Figure 5** above shows the image of a hand in the thermal image which was due to the reflection of the operators hand that was 5' away. **Figure 6** clearly shows the image of the person using the camera and the ceiling light due to the reflections of their heat images on the shiny surface of the busbar. Note that the operator's heat signature is only reflected from the busbar and not the table top or the wall behind that have high emissivity and are not reflective.

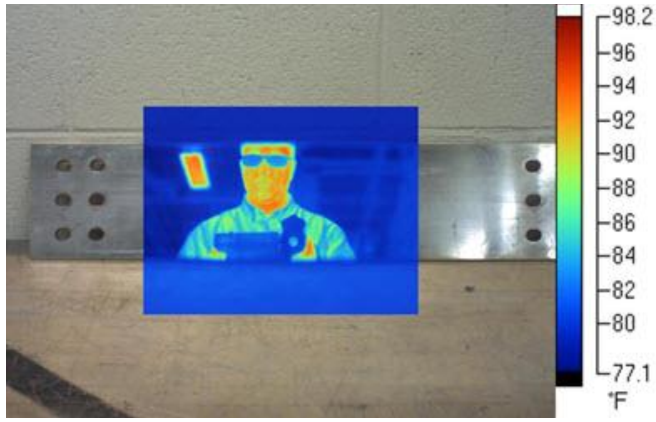
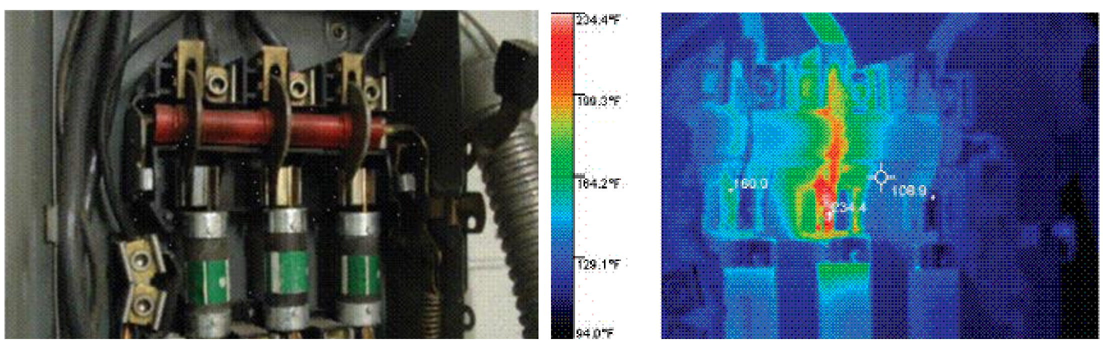


Figure 6
Thermal image showing the person using the IR camera and ceiling light due to the reflections of their heat images on the shiny surface of the equipment.

- The analyst must ensure that precautions were taken during the measurement phase to reduce this effect; either by using black paint/tape as detailed earlier or by choosing the measurement angle carefully to try and eliminate these reflections. Some modern cameras also have the option to set ambient temperature and compensate for the reflected apparent temperature.
- Blackbody effect: A blackbody is an ideal device that absorbs all energy that is incident on it, and is an ideal emitter[14]. So in some cases, if some equipment happens to simulate a blackbody, then the effective emissivity is greatly increased and the equipment might appear hotter than it actually is. For example, a disconnect switch with shiny blades and narrow gaps between the blades might simulate a blackbody as shown in **Figure 7**[15].



Power disconnect with knife blade connectors

Corresponding thermal image

Figure 7
The proximity of the shiny metal blades with narrow gaps simulates the blackbody effect with increased effective emissivity making it appear hotter than it may actually be.

- This possibility that there could have been a blackbody effect should be taken into consideration while analyzing the images.

Thermal Conductivity

The ability of a material to conduct heat is measured in terms of its thermal conductivity. Different equipment is made of different groups of materials that may have varying thermal properties. For instance, insulation tends to heat up slowly, while metals heat up quickly. So the same issue could cause different temperature rises in different materials leading to large temperature differences in certain situations, and might show misleading results.

[14] Siegel, R., and Howell, J. Thermal radiation heat transfer. Taylor & Francis, 2002.

[15] Clausing, L.T. Emissivity: Understand the difference between apparent, actual IR temps. http://www.reliableplant.com/Articles/Print/14134

Temperature readings

All scan results show total temperature readings (i.e. a sum of ambient temperature and temperature rise) while most industry standards express limits only in terms of the temperature rise over ambient temperature. Thus, ambient temperatures should be noted while taking thermal images, and should be accounted for while calculating the temperature rise in the equipment before comparing it to the standards. For example, if the ambient temperature was 73°F, and the temperature of a measured component is 193°F, then the temperature rise in the component is 120°F. This temperature rise should then be compared to the standards, after converting to °C if needed, to ensure that it is within limits.

Industry standards

Of course, industry standards for temperature requirements should be adhered to appropriately. It is advisable to maintain a list of common temperature limits listed in standards in °C as well as °F for ease of use. Some common equipment for which it is handy to have ratings readily available are:

- Plated busbars
- Cable connections
- Conductor insulation, and
- External metal parts on the outside of equipment that are accessible to personnel

NOTE: It is important to remember that UL and ANSI standards do not limit temperatures of metal materials that are not current carrying parts located on the inside of equipment/enclosures that are not to be touched during normal operation. However, of course, these temperatures should be maintained such that these internal metal parts are safe and do not damage themselves or other nearby parts.

Sanity check

Lastly, all readings should be double-checked to make sure they seem realistic. For example, consider the image shown in **Figure 8**.

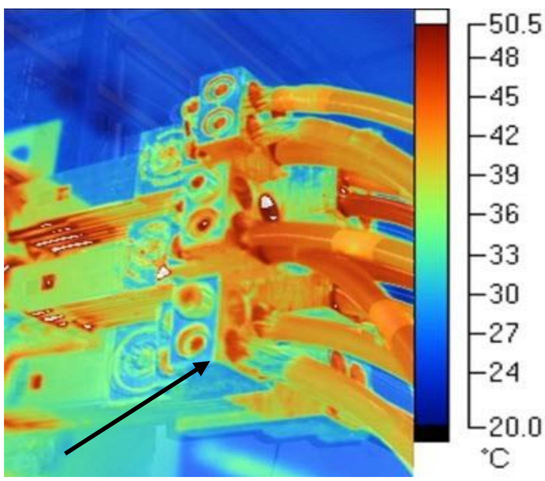


Figure 8
A thermal image showing adjacent sides of a lug in different colors as an example that further analysis of the equipment is required to understand this image.

In this thermal image, for the lug indicated by the arrow, one surface appears blue while the adjacent surface appears red. However, it is not realistic for a lug such as this to have a wide temperature difference on two surfaces so close to each other. On further review of the equipment it is found that the lug is in fact a shiny aluminum lug and this is due to the effect of emissivity.

Errors in temperature measurement could occur not only from errors in method, as noted in all the points above, but also from errors in the imager itself, for example, wrong calibration. Often, observing temperature trends in the same equipment over time eliminates some factors that hinder thermography scans from obtaining accurate temperature readings. Seeing temperature rises in these trends often helps identify potential issues that can be further investigated. Measurements from other preventive maintenance techniques must be referred to as well before making conclusions.

Conclusion

Electrical Preventive Maintenance programs (data trending) play a very important role in the effective functioning of large electrical systems. If one is able to identify potential problems before they become critical, then one can prevent the electrical system from posing hazardous threats to infrastructure and personnel by scheduling a controlled shutdown, and also prevent costly equipment failures and breakdowns. Infrared thermography is an extremely useful component of such EPM programs as it provides a way of testing for such potential problem situations with minimal intervention.

Of course, as is the case with any diagnostic tool, IR thermography can result in a large number of false positives if the practitioners are not careful, both in the image collection stage and in the image analysis stage. This is mainly because electrical equipment is always appropriately hot, and so some hot-spots are inherent in a thermal image. It is important to understand that since a large number of influencing factors affect the results of an IR thermography scan, just observing hot-spots in a thermal image does not necessarily indicate a problem. Thus, the effective use of IR inspection requires a great measure of skill, training, interpretation, and understanding.

The goal of this document is to highlight the most vital areas in both the data collection and interpretation phases of IR thermography, and provide the reader with some best practices at each stage. We also endeavor to make accessible a check-list of the intricacies an IR thermography user should become familiar with to fully harness the power of this extremely effective imaging paradigm. Our hope is that this information will aid the practitioner in making an accurate judgement as to whether an observed hot-spot is more likely to have been caused by an anomaly, or, by an error during the collection or diagnosis of data. In the end, it is a combination of a powerful diagnostic tool and a well-informed practitioner that provides real value in preventive maintenance, and helps drastically reduce the frequency of equipment breakdown in a power system.

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About the authors

Jyo Chandrapati received her B.Tech. degree in Electrical Engineering from V.J.T.I., Mumbai, India in 2008, and her M.S. in Electrical Engineering, specializing in Power and Energy Systems, from University of Wisconsin - Madison in 2010. She also completed the Energy Analysis and Policy certificate program from The Nelson Institute for Environmental Studies at University of Wisconsin - Madison in 2010. Ms. Chandrapati joined Schneider Electric in 2010 and is currently a Sr. Power Systems Engineer in the Engineering Services division. She is a Professional Engineer licensed in the state of Wisconsin, Maine, and Vermont.

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Appendix

When energy is incident on some equipment, some of this energy is absorbed, some is transmitted, and the rest is reflected. This is described by the Total Power Law as

$a + t + r = 1,$

where a = fraction absorbed
t = fraction transmitted
r = fraction reflected

Also, by what is often called as Kirchoff's Law, the relationship between an object's ability to absorb and emit radiation is given as

$a = e,$

where e = fraction emitted

So, by combining the above two equations we can see that there are three sources of thermal energy that radiate from any given object and are detected by a thermal imager. These three sources of energy are emitted energy, transmitted energy, and reflected energy, and all three of them should be accounted for while analyzing the image.

For a piece of equipment that is made of opaque material like steel, transmission of energy through the equipment is zero (i.e. t = 0). Note that we have

$e + r = 1,$

for an opaque object.

Thus, it is seen that if an object is highly reflective, it will be less emissive and vice versa.

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