Detecting Abnormal Heating of Earth Rod by Infrared Technology

Sherub Tharchen and Rabi Pradhan
Center of Excellence in Vibration and Thermographic Analysis (CoEVaTA)
Chhukha Hydropower Plant, Druk Green Power Corporation,
Chhukha: Kingdom of Bhutan

ABSTRACT

In an electrical system, grounding is of paramount importance as lightning, line surges, or unintentional contact with higher voltage lines can create dangerously high voltages in electrical distribution systems. Grounding provides an alternative path around the electrical system of homes and workplaces, minimizing damages. Likewise, earthing rods dedicated to the 11 kV bus ducts are installed to control surge voltage in the underground powerhouse at the Chhukha Hydropower Plant.

This paper discusses using infrared technology to detect abnormal heating of the earthing rods after twenty-five years of operation. Electromagnetic radiation from the 11 kV bus conductors is the root cause of the abnormal heating. These earthing rods have reached temperatures as high as 107^0C and are consuming about 344 watts of power in total in the vicinity. The radiation generated from the four earthing rods in question totals 4492 W/m^2 and differentiates the changing temperature gradient corresponding to the level of energy transmitted through the system.

The paper highlights the benefits of infrared thermography for condition monitoring to detect incipient malfunctions and anomalies. The temperature rise in the vicinity due to the heat dissipation from the earth rods is discussed along with the discrepancies found as a result of using different earth rod materials.

INTRODUCTION

Chhukha Hydropower Plant is a run-of-river scheme hydropower station located on the Wangchhu River in Western Bhutan. The four generating units of 84 MW each were commissioned between 1986 and 1988 and it is the oldest mega power project in the Kingdom of Bhutan.

The four generators produce a combined voltage of 11 kV which is routed through an enclosed bus duct to 35 MVA generator transformers where it is stepped up to 220 kV. The power is then sent to the outdoor distribution yard through Low Pressure Oil-Filled (LPOF) cables.

THERMOGRAPHY AS DIAGNOSTIC TOOL

In a power plant, loose connections and overheating can eventually result in catastrophic failure. These failures not only result in high generation losses, but can also pose a risk to equipment, facilities, and human lives. Thermographic monitoring and analysis is an effective predictive maintenance tool to prevent such failures because mechanical or electrical breakdowns are often preceded by changes in their operating temperatures, which are not visible to the naked eye.

Thermographic analysis provides a high resolution, non-contact means of monitoring by detecting and highlighting the differences in surface temperature. Thermal imaging can help identify overheating, loose connections, improper electrical maintenance, excessive machine operation, and many other common problems. Infrared is fast becoming a standard diagnostic tool for manufacturers and electricians looking to identify poor connections, arcing, heating, phase imbalances, and overloading [2]. Any electrical defects that result in the generation of heat can be readily identified using infrared techniques. As a bonus, the analysis can be carried out from a safe distance while the equipment is in service, thereby preventing machine downtime. At Chhukha and for other clients, The Center of Excellence in Vibration & Thermographic Analysis uses a portable, high definition infrared camera designed for inspection of electrical and mechanical equipment as a significant tool in its predictive maintenance program [1].

THE PROBLEM

At the Chhukha Hydropower Plant, the temperature inside the unit control gallery commonly reached as high as 40°C when the four generating units were loaded to full capacity. These inexplicably high temperatures had plagued the plant for years and made working conditions quite uncomfortable despite the installation of a ventilation system. Engineers, supervisors, and technicians were astonished when infrared technology, along with the implementation of a predictive maintenance program, revealed that the problem arose from abnormal heating of the earth rods used as a grounding system.

In an electrical system, grounding is very important. Lightning, line surges, or unintentional contact with higher voltage lines can cause dangerously high voltages to the electrical distribution system. Grounding systems provide an alternative path around the electrical system of homes or workplaces and minimize the damages.

Analysis of the thermal anomaly revealed the root cause of the elevated temperature of the earth rods: electromagnetic radiation from the 11kV bus conductors. An in-depth discussion follows.

DISCREPANCIES IN USING DIFFERENT EARTH ROD MATERIALS

The earth rods used at the 11 kV bus duct are made of different materials such as aluminum and mild steel. All of these rods, whatever their composition, are subjected to the same amount of electromagnetic radiation from the 11 kV bus conductors. The rods are supposed to heat equally, yet the mild steel earth rod (Figure 1) exhibited a higher temperature.

The likely reason is the differences induced by eddy currents in non-ferrous and ferrous metals. Aluminum is a diamagnetic material that has no magnetization properties; instead, it repels the magnetic field and thereby creates no induction of current. Mild steel, on the other hand, is a ferromagnetic material that can be magnetized easily and readily induces current.

Magnetism and electricity cannot be seen, but can be known only through the effects they produce such as heat and light or by attraction or movement of materials. When induced current flows through the mild steel earth rod, the flow of induced current is restricted due to the resistive properties of the rod. The restricted current leads to development of heat ($W=I^2R$).

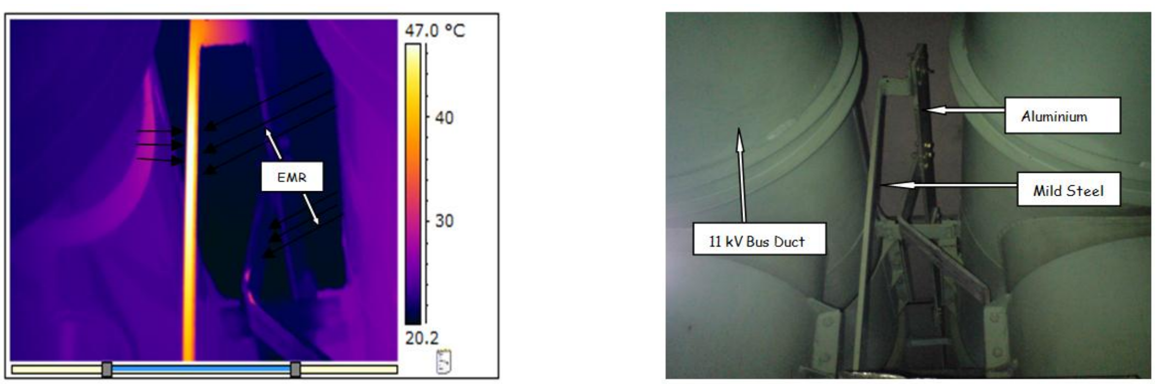

Figure 1. Left, thermogram of an earth rod; right, control visual image of the same rod.

COMPARISON OF THERMOGRAMS

Thermal images were obtained at charged and shutdown conditions. Significantly, there is no indication of thermal anomalies when machinery is in shutdown; the thermal pattern is equivalent to surrounding the ambient temperature (Figure 2, left). In the thermogram on the right, taken during charged conditions, the changing temperature gradient reflects changes in the level of energy transmitted through the system.

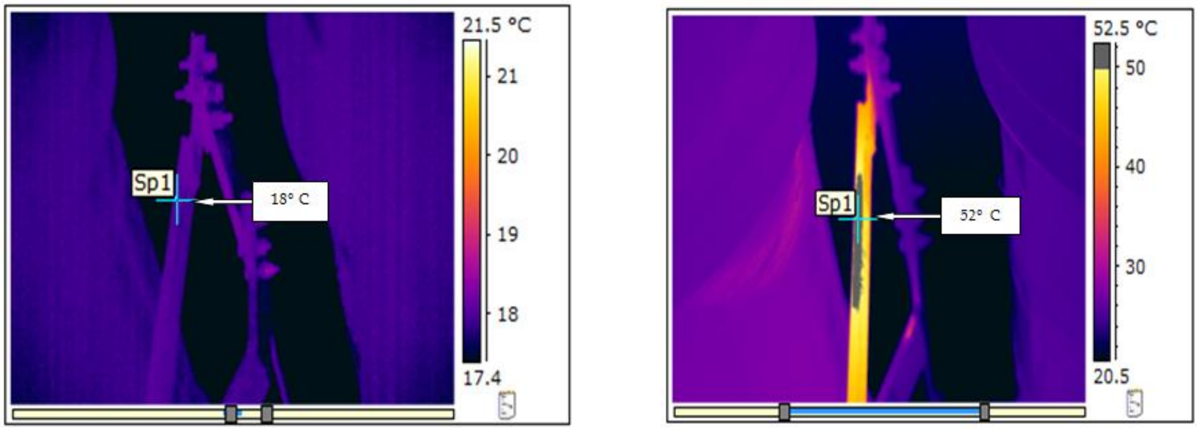

Figure 2. Left, thermogram taken during shutdown conditions; right, thermogram taken during charged conditions.

ELECTROMAGNETIC RADIATION

Electromagnetic radiation (EMR) is a form of energy emitted and absorbed by charged particles, which exhibits wave-like behavior as it travels through the space. These electromagnetic waves, like all waves, can undergo reflection, refraction, absorption, transmission, emission, interference, and diffraction.

EMR has both electric and magnetic field components [3-5]. These magnetic and electric fields become weaker as the distance increases from the source (Figure 3). The intensity of electric and magnetic fields vary in a sinusoidal fashion at a frequency determined by the oscillation of the radiation source [2].

Electromagnetic radiation carries energy sometimes called radiant energy which may be imparted to matter with which it interacts. According to the law of thermodynamics, energy can be neither created nor destroyed. The total energy of an isolated system remains the same. However, energy can change forms, and energy can flow from one place to another.

In the case of earth rod heating, the electromagnetic radiation energy produced from the charged 11 kV conductors is imparted to the earth rods and converted to thermal radiation energy when it interacts with the molecular particles of the earth rods (Figure 3).

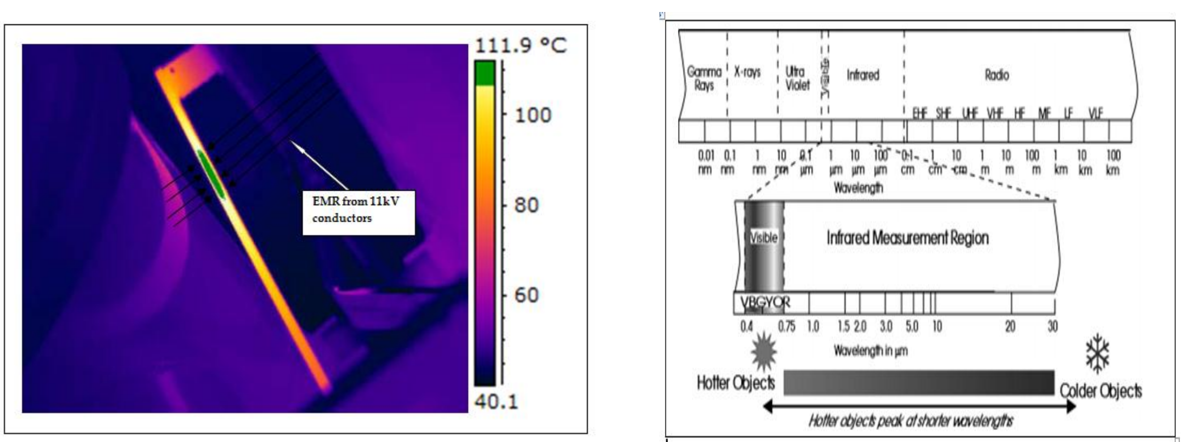

Figure 3. Left, thermal image showing the EMR from the conductors; right, diagram of infrared radiation in the spectral region [7]

INFRARED RADIATION

Any type of electromagnetic energy can be transformed into thermal energy in interaction with matter. Thus, EMR can "heat" a material when it is absorbed (Figure 3). Earth rods consist of charged particles bonded together in different directions. With incident electromagnetic radiation, these charged particles begin to oscillate and gain energy.

The ultimate fate of this energy depends on the situation. It could be immediately re-radiated and appear as scattered, reflected, or transmitted radiation. It may also get dissipated into other microscopic motions within the matter, come to thermal equilibrium, and manifest itself as thermal energy in the material [5].

All objects with a temperature above absolute zero emit infrared radiation as a function of their temperature and emissivity. Infrared energy is generated by the vibration and rotations of atoms and molecules. The higher the temperature of an object, the more the motion and hence the more infrared energy is transmitted.

As energy is radiated away from matter, the resulting radiation may subsequently be absorbed by another piece of matter, with the deposited energy heating the material. Thermal radiation is an important mechanism of heat transfer.

IR radiation is electromagnetic energy in the spectral band roughly from 0.75 μm to 100 μm. The human eye is responsive to the only visible region of the spectrum from about 0.4 to 0.75 μm. Thus, most infrared radiation is outside the visible range. However, infrared emissions can still be focused by an optical system onto a detector in a fashion similar to human eye. This detector is an infrared sensor. Infrared radiation, like all electromagnetic radiation, obeys the following law:

$$\lambda f = C \text{ (constant)}$$

Where:

λ = Wave length
f = Frequency
C = Velocity

The greater the frequency, the smaller the wavelength will be. Based on the applications, IR imagers are classified broadly into three categories (i) short wave (0.75-2.0μm) (ii) mid-wave (2.0-5.0μm) and (iii) long-wave (8-15μm) cameras. For applications such as the detection of the abnormal heating of the earth rod, cameras in mid and long wave range are most suitable.

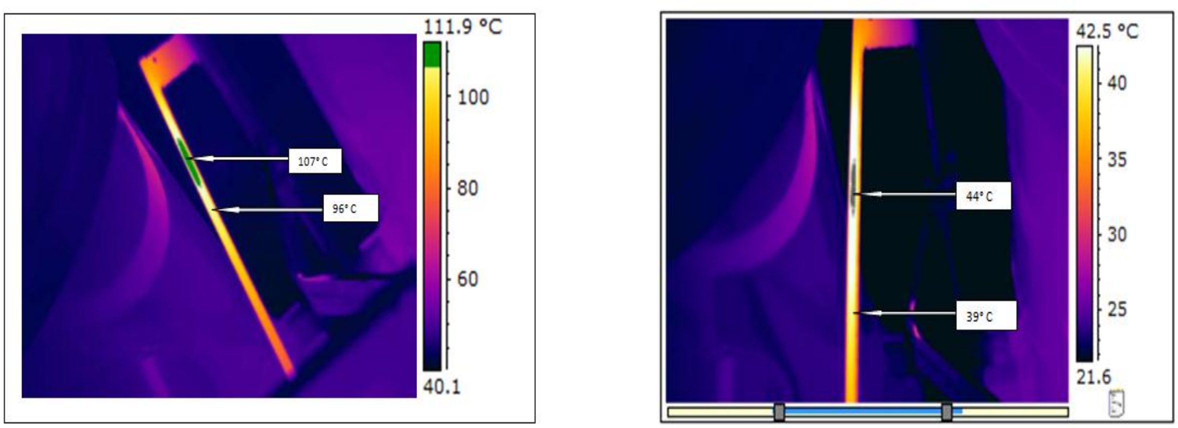

Figure 4. Left, thermogram of a heated earth rod at 92 MW; right, thermogram of same rod at 50 MW

In Figure 4, in the left thermogram, a temperature of 107°C marked the hottest point. In the right image of Figure 4, the midpoint of the earth rod had a reading of 44°C as highlighted by the isotherms. The heat is generated at the midpoint and conducted to other areas. The hottest spot is more accurately adjacent to the HV line. The electromagnetic radiation or magnetic field at the midpoint is very strong compared to other areas due to the strong magnetic field. The electromagnetic radiant energy decreases as the distance increases from the source. (Expressed differently, the shorter the wavelength, the more the power to heat the objects. The longer the wavelength, the weaker the power to heat the objects.)

The hottest spot temperature at the midpoint was compared when the machine was loaded at 92 MW and 50 MW (Table 1). The reason behind the huge temperature difference could be due to difference in magnetic field strength or electromagnetic radiation.

Load (MW)	Temperature (°C)
92	107
50	44

Table 1. Comparison of hottest spot temperatures/

HEAT DISSIPATION AND TEMPERATURE RISE IN THE UNIT CONTROL GALLERY

As per Lenz's Law, when current flows through the conductor, it creates a magnetic field around the conductors. The intensity of the magnetic field around the conductor is directly proportional to the amount of current flowing through the conductor. The stronger the electromagnetic field, the higher the current will be induced on the surrounding objects due to mutual induction.

The earth rod located in between the 11 kV conductors is subjected to a very strong magnetic field and the maximum inducement of current. The induced current leads to heating of the earth rod due to resistance of the earth rod ($W=I^2R$). The infrared radiation from the heated earth rod is dissipated to the surrounding area, thereby increasing the air temperature inside the unit control gallery.

The temperature inside the unit control gallery can reach as high as 40°C when the four generating units are loaded to full capacity, and causes discomfort to the personnel working in the gallery. The temperature increases as the load increases and vice-versa. Despite the adequate air conditioning systems installed in the gallery, the high room temperature remains intractable.

When the unit is loaded at 92 MW, radiation energy of 1123 W/m^2 is generating from each 11 kV conductors. An individual earth rod generates infrared radiation energy as high as 1123 W/m^2. The radiation generated from the four earth rods adds up to 4492 W/m^2.

The radiation energy is calculated using Stefan Boltzmann's Law [6]:

$$\mathbf{WRB = \varepsilon * \sigma * T^4}$$

Where;

ε = Emissivity
σ = Stefan-Boltzmann's Constant
K = Kelvin (273K+ º C)
WRB = Real Body Radiation

With the maximum temperature of the earth rod at 107°C, it is evident that some source of heat energy must be responsible. The wattage required to heat the earth rod is calculated as follows [10].

Weight of materials (lbs) * Specific heat (Btu/lb°F) * Temperature rise (°F)
3.412 BTU/watt hr. * heat-up time (hr.)

The power loss in heating one earth rod is about 86 watts, which is quite negligible as compared to the generation of each unit. In total, the power consumed is equal to the power required to light eight electrical tubes of 40W each.

The temperature rise inside the gallery may not solely be due to the infrared radiation from the heated earth rod. There are several other heat sources, such as the excitation transformer, field breakers, and the unit control panels. With all of these factors in mind, additional split-type air conditioning plants were installed to help maintain a comfortable working environment.

SUMMARY AND CONCLUSIONS

Based on the analysis and references, electromagnetic radiation from the 11kV bus conductor was diagnosed as the principle cause of the unusual heating of the earth rods to as high as 107°C, consuming about 86 watts of power each and producing radiation up to 4492 W/m^2.

In addition to creating uncomfortably high working temperatures, extremely high power electromagnetic radiation such as we found at the Chhukha Hydropower Plant can cause electric currents strong enough to create sparks (electrical arcs) when an induced voltage exceeds the breakdown voltage of the surrounding medium. These sparks can then ignite flammable materials or gases, possibly leading to an explosion (Figure 5).

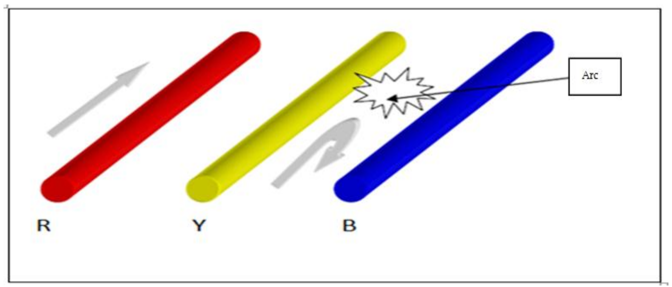

Figure 5. Arc due to strong electromagnetic radiation [8]

The combination of long-term worker discomfort and potential for catastrophe were together significant enough to cause us to recommend that the location of the earth rods be changed to avoid abnormal heating.

Keep in mind that the correct use of infrared can mean huge savings for a company, but identifying a problem is only half the solution. Improper corrective actions and failure to understand the proper solution not only cost money, but can also, and perhaps more importantly, damage reputations.

ACKNOWLEDGEMENTS

The authors would like to thank the Management of Druk Green for the motivation in writing this paper and Chhukha Hydropower Plant for the support. The authors would also like to thank colleagues at the Generator Maintenance Unit and Operation Division at CHP for their support and cooperation in allowing inspection of the earth rods under varying load conditions. Finally, the authors would like to thank Tenzin, Head CoEVaTA for his guidance and inspiration in writing this paper.

ABOUT THE AUTHORS

Sherub Tharchen and Rabi Pradhan have been using thermal technology for the past two years. Both are ITC-certified Level 1 thermographers (ISO 9001) and hold Certified Magnetic Particle Inspection Level II (SNT-TC-1A of ASNT) and are Certified Vibration Analysts, Cat. II (18436:2). Both authors have diplomas in electrical engineering and over 10 years of experience in the operation and maintenance of hydropower plants. They may be contacted at sherubtcoe@gmail.com1 and ravicoevata@gmail.com.

REFERENCES

1. Ralph J. Michael, Exelon Nuclear – LaSalle Station "Power Plant Thermography – Wide Range of Applications". InfraMation 2004 Proceedings, ITC 104A 2004-07-27.
2. ASNT LEVEL II, Study Material in Magnetic Particle Testing, SNT-TC-1A.
3. IRT Surveys Ltd. http:/www.irtsurveys.co.uk/precditive-maintenance/electrical-equipment, February 28, 2012.
4. Field Service Memo, Electromagnetic radiation and how it affects your instruments". May 20,1990OSHA Cincinnati Laboratory (now the Cincinnati Technical Center) Cincinnati, Ohio.
5. [D1] ANSI/IEEE 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms, 1984, page 328.
6. [C1] Jordan, Edward C. and Balmain, Keith G., Electromagnetic Waves and Radiating Systems, Prentice-Hall, Inc., 1968, Pages 103, 118, & 120.
7. Infrared Training Center, Thermography Level-1, Course Manual, Chapter 11, page 72.
8. Manuals, Hand Book TR-107142, "The Infrared Spectrum" Pages 2-9.
9. Holiday Tony "Is Electrical Switch Gear Safe" Hawk IR International Ltd. InfraMation 2004 Proceedings, ITC 104 A 2004-07-27.
10. TEMPCO Electric Heater Co