Advantages and Limitations of Thermography in Utility Scale Solar PV Plants

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Abstract

Thermal Imaging has always been used in military applications along with night vision, when there is no sun. Now is the time we need thermal imaging technology to check the performance and find out abnormalities/underperforming areas in Solar PV power plant. While the advantages of thermal imaging are large in number, but it comes with a need of awareness of the concepts of heat transfer and fundamentals of measurement. A lot of research has been done, on how to do the thermal imaging of various type of surfaces, which have glazing or some type of coating over them. This paper tries to summarize the knowledge gained in the field of heat transfer along with the application areas where Infrared (IR) thermography can help us track down high temperature regions (hot spots) in a Utility Scale Solar PV Plant. This paper will also serve as a quick reference guide for the Solar industry engineers for a fast set up, measurement and understanding of Thermographic Instruments. For the analysis purpose, a 100MW Utility scale solar site and few rooftop solar projects in India were chosen to collect the data and for taking the measurements.

Keywords: Thermal Imaging, Performance of PV plant, Hot Spot, Heat Transfer, IR Thermography, Reference guide

1. Introduction

Numerous techniques are being used to measure the performance of components in a PV plant. Monitoring systems come into play, starting from the string level/array level data and it goes till current reaches the grid. Sensors are used to measure temperature of modules, ambient temperature, Irradiance, wind speed, wind direction and also in the electrical and electronic equipment to keep a check on the performance and operation. The solar industry has started using Infrared thermography for finding the underperformance in their modules and to narrow down the faults to specific cells (Hot Spots). It is also being used for checking the uniform oil flow in heat exchangers of transformers and check whether the oil is circulating as expected or there are regions of blockage by seeing the thermal image of the equipment. Similarly, this can be used to check spark or loose contacts at isolator or evacuations points or substation level of a solar power plant. So, a lot of early failures can be detected.

To check the performance of the components, one needs a good understanding of materials, their glazing behavior as well as knowledge of heat transfer subject. Every object can emit, reflect and transmit radiations in different band of the electromagnetic spectrum, depending on the properties of the material and the temperature of the object. Sun is emitting electromagnetic (EM) radiations in a broad range of Infrared (IR), Visible, UV and X-ray, etc. Every object above 0 K (Kelvin) emits and receives energy (Plank's Law). In IR thermography, we use the infrared emitting capacity of a body which most of the time is a strong function of temperature (Stefan-Boltzmann law). A thermal imager can capture the IR radiations emitted and can convert the IR data in high and low temperature regions using visible spectrum on our display screen.

2. Working of Thermal Imaging Technology:

2.1 Background

In the last 50 years, there have been three major developments in area of thermal imaging and these are: (1) Scanners or Scanning Systems, (2) Pyroelectric Videocon's (PEVs), and (3) Focal Plane Arrays (FPAs). FPA technology is more popular these days due to advancement in semiconductor industry and because of the accuracy possible with them. The function of the equipment is to detect the infrared radiations emitted by

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an object or equipment (known as Target). Corresponding to the Radiosity (sum of radiations, emitted, reflected and transmitted per unit surface area) of the object, there is induced voltage or change in resistance of semiconductor array. These signals are then read by the electronic circuits present in the equipment and a thermogram is created which is visible to us on the display screen of equipment (Fig. 1). Each pixel of thermogram inherits the point to point temperature measurement on the surface of the object. This is done by an array of semiconductor detectors, which are placed on a plane and are highly sensitive to temperature. More is the density of plane of the array; more will be the resolution of the thermal image and hence higher accuracy of measurement. Typical arrays used are 256x256, 320x240, etc. For the current analysis, we have used thermal equipment of Testo and Fluke companies, and used their respective software for the analysis.

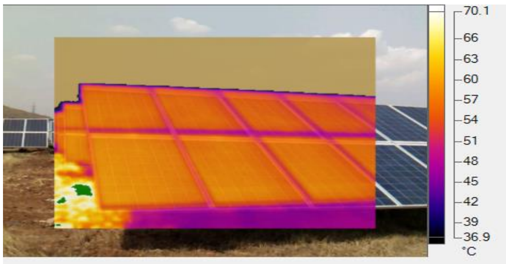

Fig.1: Thermal image distinguishing the high and low temperature regions with the help of the visible spectrum, white and yellow being the highest temperature region while black and blue indicating a lower temperature range.
(Image taken at one of the megawatt scale solar plant in India)

2.2 Sun's Spectrum

Sun has always been the source of energy for earth. From photosynthesis to blowing wind, it is all because of the sun. In recent years, we have learnt the importance of using sun's energy directly instead of stored forms like fossil fuels, as we don't have to spend extra money for their extraction and purification. We just need technology, which can convert Sun energy directly to electricity. Solar PV technology is at the forefront of all renewable energy sources. As per International Energy Outlook 2016 by the IEA, around 30% of total electricity generation in 2040 will be from Renewable sources of energy (International Energy Outlook, 2016). In another Annual Energy Outlook report 2017 of the IEA, solar capacity addition is projected to be the primary replacement of retiring coal power plants between 2030 and 2040 (Annual Energy Outlook, 2017). Utilizing sun's energy will be the most economical and most sustainable option in coming years. The more we know about the sun and the ways to utilize its energy, the better it will be for us.

The photons coming from the sun, carrying this energy, have a wavelength varying from high energy X-rays and gamma rays to visible light to the infrared and radio. However, here on earth, we receive only a certain portion of the spectrum. Sun's spectrum (shown in Fig.2) is similar to that of a spectrum of black body at 5800K as mentioned by Duffie and Beckman (Duffie and Beckman, 2013). Out of these radiations, around 44% of radiation are in visible range, i.e. 400-700 nm or 0.4-0.7 μm and 49% in the infrared region.

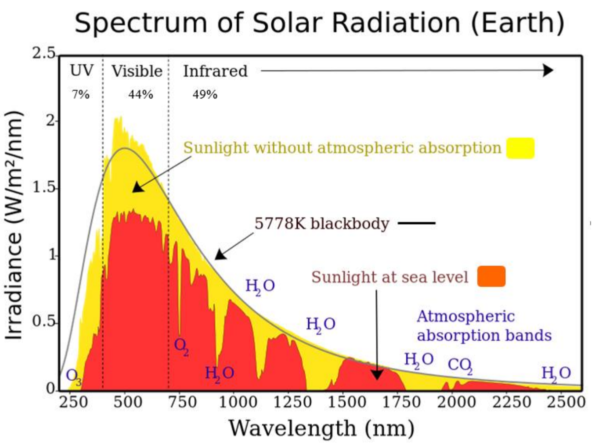

Figure 2: Sun's Electromagnetic Spectrum (Nick, wikipedia)
Image credits: Nick84 http://commons.wikimedia.org/wiki/File:Solar_spectrum_ita.svg, CC BY-SA 3.0,

2.3 Infrared Radiations (IR)

Any Radiation falling on any object is never perfectly absorbed, transmitted or reflected. Always, two or all three of these phenomena happen at once. For a typical transparent glass, 92% of the radiation are transmitted, 6% are reflected at the glass surface and 2% are absorbed. In the solar PV modules, the glass used is extra clear glass with low iron oxide content, which helps in less absorption of light. The transmission curve of glass also shows us that the glass is somewhat transparent in the short waveband and opaque in the long waveband. All these phenomena are also true for IR falling/transmitting through the glass surface.
When we see a surface, we can see the radaitions being absorbed by it along with the radiations reflected or transmitted by it. Neither the reflected nor the transmitted radiations, provide any details about the temperature of the object. Only emitted radiation coming out of a body give us a sense of temperature. This radiation being emitted by a body is directly dependent on the emissivity of the surface.
In thermography, the biggest task for a professional is to separate the reflected and transmitted part of radiation from the emitted radiations. Glasses are typically transparent to short IR wavelengths and opaque to long IR wavelengths. Our atmosphere is transparent in two regions of wave i.e. visble, infared and radio wave bands, rest of thermal spectrum is absorbed by water vapors, carbon dioxide and other gases (Fig.3).

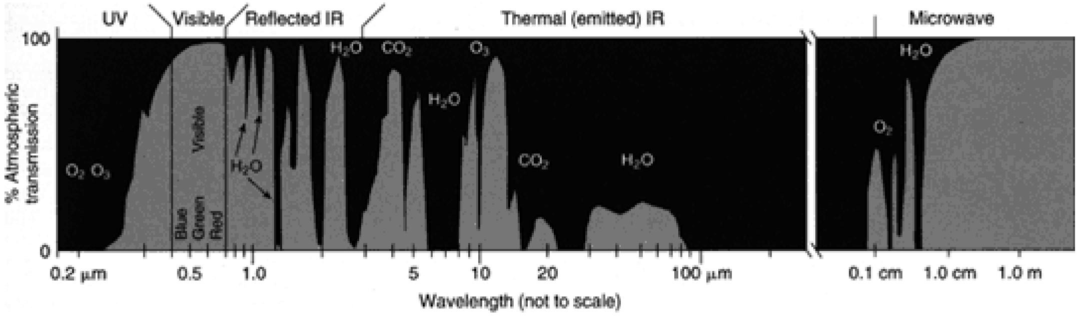

Fig.3: Absoption spectrum of earth's atmosphere. Chemical notation (CO2, O3) indicates the gas responsible for blocking sunlight at a particular wavelength. (Earth observatory, NASA)

2.4 Materials and Emissivity measurement

A black body is a perfect absorber and emitter of radiation. The emissivity of a surface represents the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. The emissivity of a surface is denoted by ε, and it varies between zero and one, $0< \varepsilon<1$. Emissivity is a measure of how closely a surface approximates a black body, for which $\varepsilon=1$ (Yunus A. Çengel, 2002).
For better measurements, we also need to know about the absorption property of a body. Absorptivity is a measure of how much fraction of the radiation falling on the object/medium is absorbed by it. Radiation falling on a surface/medium could have encountered three phenomena (a.) Absorption (b.) Reflection (c.) Transmission (explained in eq.1). The fraction of these will vary depending on property of the object/medium.
From the first law of thermodynamics we can say that,

Energy Incident = Energy Absorbed + Energy Reflected + Energy Transmitted

1 = (Energy Absorbed + Energy Reflected + Energy Transmitted) / (Energy Incident)

Or, $1 = \alpha + \rho + \tau$ (eq. 1)

Where, α is Absorptivity, ρ is Reflectivity and τ is Transmissivity of the material.

For finding the temperature of any object, there are equipment available. There are Infrared thermometers, which can give us point-to-point temperature readings and there are thermal imagers, which gives us the 2D image of the surface showing hot and cold regions with different colors/contrast. Many Instruments from various manufacturers like Fluke, Meco, Testo etc. have come into the market. But, measurements made by these instruments do not make sense till accurate values of material/media properties, external factors are given as input first.
For example: To find out any hotspot in a string or array we need to have knowledge of emissivity of silicon material (assuming multi crystalline silicon solar cells) and how the upper glazing is affecting the measurement. All the metals are good conductors of heat and electricity, so they don't emit a lot of radiation

in IR region and also they don't emit the radiation from the same place where radiation has fallen. Inside metals molecules vibrate quickly and energy gets conducted to all surrounding molecules, which results in lesser values of emittance. Metals also reflect a part of incoming energy/light falling on it. This kind of behavior is not shown by semiconductor materials. They absorb the radiation and emit it in the IR region. Most of the radiation is emitted from the same place where incident radiations fell. So, most of the time Semiconductors and insulators have higher emissive values. Table 1 lists the common materials encountered while doing thermal imaging along with their emmissivity values.

Tab 1: List of common materials and their emissivity.
(Fluke, Emissivity of materials), (Transmetra, Emissivity for various surfaces)

Sr. No.	Material	Emissivity	Sr. No.	Material	Emissivity
1	Aluminum Foil	0.04	26	Mild Steel	0.20 0.32
2	Aluminum Highly Polished	0.039-0.057	27	Paper	0.93
3	Aluminum Heavily Oxidized	0.2-0.31	28	Plastics	0.90-0.97
4	Asbestos board	0.96	29	PVC	0.91-0.93
5	Asphalt	0.93	30	Silica	0.79-0.85
6	Brick, red rough	0.93	31	Soil	0.79
7	Brick, fireclay	0.75	32	Steel Polished	0.07
8	Cast Iron, newly turned	0.44	33	Steel Galvenized old	0.88
9	Cast Iron, turned and heated	0.60 0.70	34	Steel Galvenized new	0.23
10	Cement	0.54	35	Tin unoxidized	0.04
11	Clay	0.91	36	Titanium polished	0.19
12	Coal	0.8	37	Tungsten polished	0.04
13	Concrete	0.85	38	Water 0.95 0.963	0.95 0.963
14	Cotton cloth	0.77	39	Wood Beech, planned	0.935
15	Copper electroplated	0.03	40	Wood Oak, planned	0.885
16	Copper heated and covered with thick oxide layer	0.78	41	Wood, Pine	0.95
17	Copper Polished	0.023-0.052	42	Wrought Iron	0.94
18	Copper Nickel Alloy, polished	0.059	43	Zink Tarnished	0.25
19	Glass smooth	0.92 0.94	44	Zink polished	0.045
20	Human Skin	0.985	45		
21	Ice smooth	0.966	46		
22	Ice rough	0.985	47		
23	Iron polished	0.14 0.38	48		
24	Iron, plate rusted red	0.61	49		
25	Mercury liquid	0.1	50		

Note: As we know, emissivity of a given material will vary with temperature and surface finish, the value in these tables should be used only as a guide for relative or differential temperature measurements. The exact emissivity of a material should be determined when high accuracy is required.

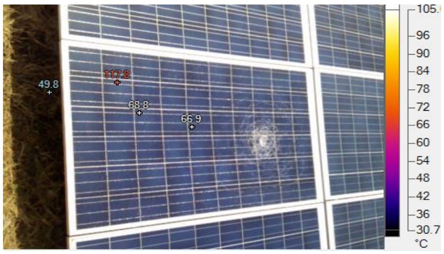

Fig. 4: Optical Image of a damaged module.

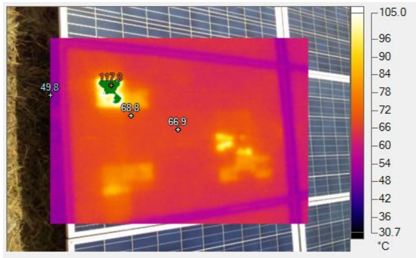

Fig. 5: IR Image for damaged module (fig.4) with hot spot and high temperature region.

In IR thermography, camera sensor takes the IR radiations emitted by a body as its input to calculate the temperature of the body. These instruments most often need the ambient temperature values for reference temperature and then calculate the temperature of materials/medium accordingly. For silicon, two values of emissivity are given in standards 0.8 and 0.9, depending on glazing. Assuming the value of emissivity as 0.8 and setting the measurement range at 35 to 75 degree centigrade in the equipment, we were able to get better results. For cross checking our measurement, we had used a thermocouple at the back of one of the solar modules.

3. Application of Thermography in Solar PV Plants

Thermal imagers will pin point us in the direction where fault/abnormality is present. By using electrical instruments like Multimeter, Clampmeter and Resistance measuring units, we can get into the root cause of an issue. Suppose there is an extra heating in one phase out of the three, thermal imager will direct us to that phase, now to find out the reason for heating, we need to check the amount of current flowing as well as the resistance in the circuit. A list of solar plant areas, where thermal imaging is used, is mentioned below:

3.1 Application area: To check underperforming solar strings and arrays:

Solar modules are the main component of energy conversion. The plant's efficiency depends primarily on this conversion process. We can also calculate overall solar plant efficiency as the product of all the efficiency in the process (as shown in eq. 2). For the efficiency calculation, we must know the losses in each step of conversion.

The losses in a solar plant are as follow:

1. Loss due to temperature (The rated power of modules is calculated at 25°C) = L1
2. Dirt or soiling on face of solar module (Often, Dirt loss=5-10% or 0.05) = L2
3. Manufacturer's tolerance (3-4% or 0.03, given by the manufacturer) = L3
4. Voltage drop through AC and DC cabling = L4
5. Inverter efficiency/loss = L5
6. Shading = L6
7. Tilt angle of the solar modules = L7
8. Orientation of solar modules = L8

Overall efficiency= (1-L1) x (1-L2) x (1-L3) x (1-L4) x (1-L5) x (1-L6) x (1-L7) x (1-L8) (eq. 2)
(GSES,2013)

Using this only, we also calculate the Energy yield of the plant,

Energy Yield = Irradiation x Module rated power x Losses (as efficiencies)

Using a thermal imager, we can calculate the thermal loss of the module and if there is any hotspot areas on the panel.

In a solar panel, generally the cell temperature is 20-25°C higher than the ambient temperature because of continuous heat generation at cell level. So, in the countries, which lie in between the tropic of cancer and the tropic of capricon, this thermal loss can reach upto 20% (considering ambient temperature can go upto 50°C). The performance of these semiconductor solar cells is highest when the temperature is 0 degree C, which is not usually the case. This is one of the reasons that a place with high radiation need not be generating the most amount of energy, compared to a place with low irradiance and low temperature.

So, thermal cameras can be used to check the healthiness of modules and for each degree higher temperature, we lose roughly 0.3-0.5% of power output of cells. The Supervisory control and data acquisition (SCADA) systems used currently will tell us the strings which are not giving full output and combined with thermal cameras we can easily distinguish the faulty or damaged module which are making the loss.

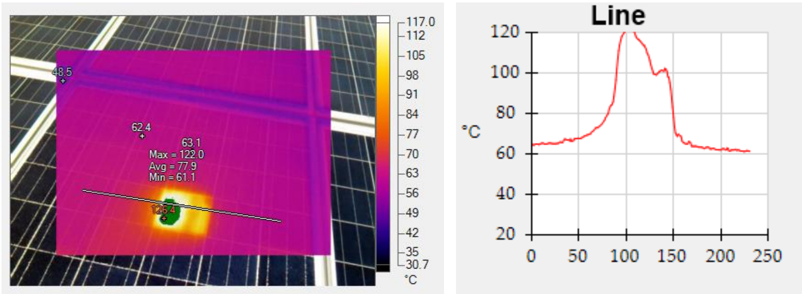

Fig 6: The image on left shows the hot spot on a module and the damaged cell with temperatre going upto 120°C (Shown in right side figure with line graph)

3.2 Application Area: String Monitoring Unit (SMU)/ String Combinor Box Monitoring (SCB)

These days SCADA systems are primarily used to check the string current in a large solar plant. Burning issues in SCB/SMU are also common. At places around the world, fire incidents have also occurred because of overheating issues at the terminal inside the SCB. On many occasions, it is found that connecting terminals/joints are getting heated, but the temperature is not high enough that they will glow brightly and it will become visible to the naked eye. The temperatures will go upto 200-250°C before the melting and burning of plastics/rubber happen on wire insulation. Most plastics used are fire retardant but not fire proof, so till date, early detection is the only key to avoid these accidents. Thermography being a non-contact type technique, we can easily distinguish the overheated points, which may be because of any of the reasons like, loose connection, dust in between the joints, some malfunctioning etc. The same is true for isolator panel boxes also on AC and DC sides.

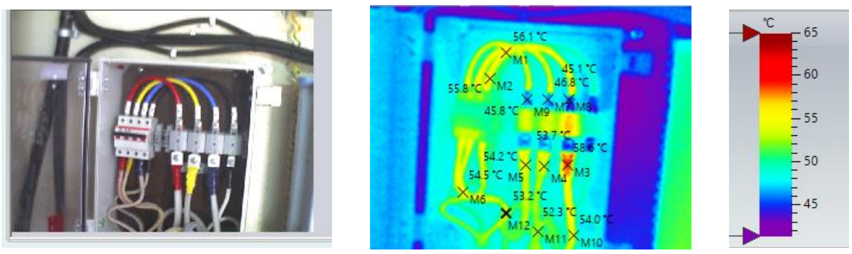

Fig 7: Normal and Thermal image of a typical Isolator Panel of a rooftop solar plant. In centre image we see that blue phase wire temperature is roughly 5°C higher than wires of remaining two phases.

Action plan for relative temperature difference between phase connections:

40°C or more : Failure can happen at any time and corrective measure should be taken immediately

20°C-40°C : Corrective measures to be taken at earliest to avoid failure in coming hours/days

20°C : Corrective measure required to prevent from failure in coming weeks

Below 20°C : Chance of failure; measure should be taken in next scheduled maintenance activity

3.3 Application Area 3: Power Conditioning Unit (PCU) / Inverter Level Inspection:

Inverters available in the market now (2016 onwards) have efficiencies of 95-98%. The remaining are the conversion losses which happen in electrical and electronic components of the inverter. High quantity of current coming from PV panels enters the inverter as Direct Current (DC) and we get 3-phase Alternating

Current (AC) at the output. In recent inverter models, it is hard to see insulated-gate bipolar transistor (IGBT) from outside, which is responsible for DC to AC conversion. This is adopted because of safety features and Ingression protection standards like IP 65, IP 66 etc. In some older Inverter models (prior to 2014-15), checking healthiness of IGBT's against overheating was possible with thermal cameras. We can also check the heat emitted by bus bars, circuit breakers and at other connection points and can tell whether there is something abnormal or not. In some cases, because of less space below Inverters and Junction boxes, wires are bent in 'U' shape, This causes a lot of resistance to current flow and hence heating of wires. We can inspect such areas with thermal cameras.

3.4 Application Area: Switchyard and Substation Area:

Switch yard is the area, where the same power, which is generated by a solar plant, is transmitted to the state electricity board substation or transmission company. Substation steps up or steps down the voltages coming from the generating station. In both substation and Switch yard areas, thermography has huge application because of the criticality of the equipments used. The components include circuit breakers of various types, isolators, isolated phase buses, T joints, straight joints, bolts on bus bars, various fuses, transformers, etc. Heating of bolts, moving contact parts, etc. in substation are often checked with thermal cameras. The fault or failure of any of the components can lead to significant breakdown and hence loss of power. To confirm the healthy functioning of these areas, in terms of smooth power evacuation without excessive heat being generated on isolators, at bus bar connection points, we use thermal cameras. Depending on the material used like bus bars are generally aluminium rods; we can set our instrument for the measurement. For high voltages, aluminium is the most preferred choice because of conductivity, strength and corrosion resistance.

This not only saves time but also gives us confidence about the smooth operation of the plant.

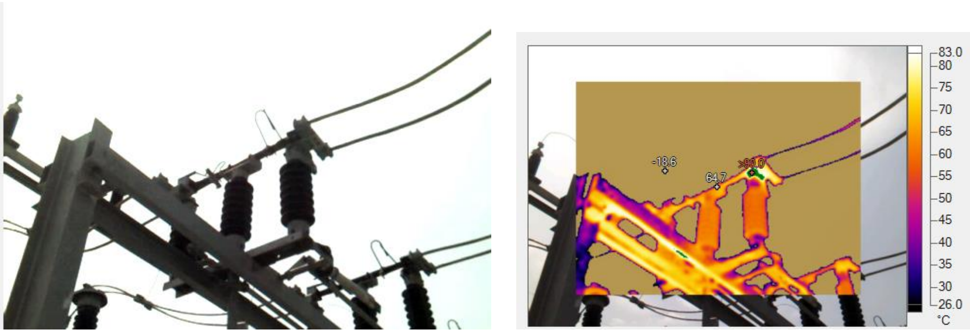

Fig 8: Visible and infrared image of isolator and bus bars.

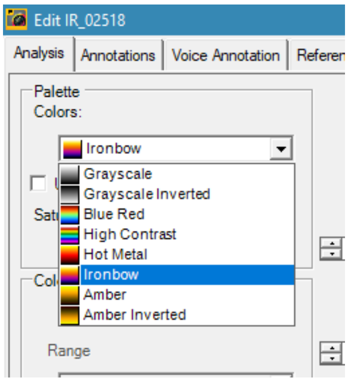

Fig 9: Palette options available in softwares to have better visual effect. (Screen: Fluke smart view software)

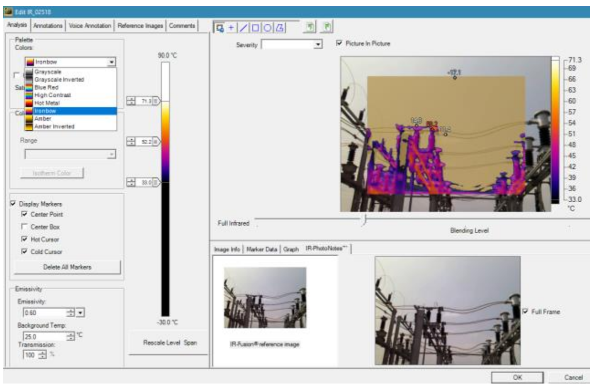

Fig 10: Fluke Smart view software window with image of a typical isolation yard.

Note: When using the software for analysis, we need to put correct emissivity one by one for materials under observation to see correct values of temperature. One should not conclude on basis of half-baked information. One can also choose different kind of palettes as per one's ease and visual advantage (Fig 9).

4. Advantages and Limitations of IR Thermography

4.1 Advantages of Thermography (Tequipments.net)

- It uses non-contact type of measuring technique, which makes it safe.
- It is fast, accurate and easy to use.
- It helps in detecting situations of electrical unbalance or overloads.
- It can be used for electrical, mechanical and other building envelope related work.
- It helps in fast identification of loose, corroded connections even if they are not visible to naked eye.
- It helps in developing the Inspection program for various equipment and machineries.
- It can be driver in making predictive and preventive maintenance schedules.
- It can be used to check, heating in electronic circuit board and narrowing down to faulty area.

4.2 Limitation of Thermography

- High reflecting metals: Using thermal imaging becomes tricky, when one takes measurement of isolation yard on a sunny day. Unlike coal thermal stations or other energy generating stations, in solar plants peak generation is in the hours, when the sun is shining bright. At this point of time, the metals also reflect a lot of visible light. The expert has to carefully choose an angle, where sun interferes least and try to get more radiations, which are emitted by the target equipment under consideration. This can be done by varying the emissivity value or using some correction factor.
- Trapping of IR radiation inside glass enclosures: Most of the thermal cameras available today can take the measurement in short and medium infrared region. Filters are available to take care of interference by glazing and other radiations.
- Weather dependence in solar plant also plays a role. Recommended time for taking measurement is peak sunshine hours. (between 11 am -2 pm in India)
- Significant change in readings, when angle of measurement change. The recommended practice is to take the measurement at an angle of 90 degree (normal) to the surface of object. If we take the image at acute angles, then, the measurement will be incorrect.
- When wind blows over a surface, a boundary layer is formed which effects the heat transfer. Recommended practice is to take the measurement in still air conditions and at steady state conditions.
- IR themography takes the instantaneous measurement and not the gradient. In some cases, when temperature is rising and falling with time, we cannot find the rate of change of temperature directly. In those areas, thermocouples are best suited to analyze the trend with time.
- For small rooftop solar plants, the cost of thermal equipment is high in comparison to the investment one has done. So, it is common practice to ask an O&M company, which has taken annual maintenance contract to do the themographic exercise once a year. This has more application in large scale utility solar plants, where electricity is directly going to national grid and one can not afford any failure in any components.

4.3 Other Application Areas:

- Used commonly by Energy Auditors to find the areas of heat loss and poor insulation in processing industry and manufacturing industry.
- Used to find oil/gas leakages from the vessels.
- Used by civil work departments and building professionals to check the structural integrity and sometimes the moisture inside the roof/wall etc.
- Military use this technology along with night vision cameras in aircraft and auto guided missile systems.
- Used oftenly, in industries where lot of motors and rolling machines are present. This technology helps in planning their maintenance schedules.

5. Conclusion

As solar energy sector has shown its dominance in last few years, with accelerated growth rates; in coming years, our life will be surrounded by equipment, machines and homes, running completely on solar energy. This paper has tried to summarize the learning from megawatt scale solar plants in India, along with the general understanding about IR thermal imaging technology. Most suitable person for thermal inspection activity will be an engineer with basic understanding of concepts of heat transfer like radiosity, boundary layer along with some knowledge of material science. The awareness of parameters like background temperature, ambient air temperature, relative humidity, information on effect of wind or convection heat transfer, emissivity properties, effect of sun, ideal distance of target, angle of incidence, will make the measurement highly accurate. This paper has tried to touch upon these above parameters with field examples and learnings from the SPV power plant. Few general thumb rules are also suggested, on the how to decide the criticality and frequency of maintenance activity, based on the temperature readings (sub-section 3.2). This paper will also serve as a reference guide, for using thermal imaging in different solar power plants and other areas of energy efficiency.

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