Thermography as Automatic Diagnostic Tool For Electrical Substations: A Review

J. Amjad[1], M. Abrar[2]

[1,2]Electrical Engineering Department, UCE & T, Bahauddin Zakariya University, Multan
[1]jawadamjad93@gmail.com

Abstract-Temperature and resulting heat signatures are pragmatic indicators of the healthiness of electrical equipments employed in substations. The thermal heat, resulting due to losses induced by square of current flowing through switchgear and any irregular pattern, can be appropriately measured and detected by infrared based non-destructive and non-contact type thermographic technique to detect any anomaly present in the electrical substation. Thermographic process can detect any irregular and abnormal conditions in the substation without having need to impede productivity thus enhancing the overall reliability, safety, availability of power system along with reducing maintenance costs by predicting the fault in the electrical substation. The different kinds of problems encountered in the substation equipment along with the constraints of thermography have been presented. The main focus of this paper is on review of image processing methods which essentially automate the process of fault detection in substation. These image processing methods augment the thermographic process with advantages of negating the possible effects of human errors, suppressing the external noise signals and also speeding up process of pinpointing the faulty area in the target image which is core objective of thermography of substation because manual analysis is laborious and error prone. In addition, due to its widespread usage as a condition monitoring tool, the applications of thermography in different fields of life have also been discussed.

Keywords-Pragmatic, Thermographic, Productivity, Image Processing, Automate.

I. INTRODUCTION

The infrared thermography (IRT) is a technique of measuring the temperature of materials by inspecting them with the help of some thermal imaging means. This inspection is performed to make a thorough observation and inspection about the operating condition and service life of the material. These thermal imaging devices actually measure the radiations emitting from the surface of the material upon which the inspection is being performed. These thermal imaging devices are designed to measure the radiations and convert them into useful observations. As the name implies they measure the infrared energy emitting from the material. Every material above absolute zero (0 Kelvin) releases heat in some form of radiations.

Thermography has emerged to be an excellent technique for monitoring and diagnosis of substation equipment. In order to make a correct and thorough diagnosis of substation equipment, it is imperative to have knowledge about the component identification and thermal signatures to be obtained from different substation equipment [i].

One of the main advantages of thermal infrared thermography is that all the electrical equipments in a substation get heated to unbearable extent before they become permanently damaged, that's what thermography works on. Its process, advantages in the rural utility have been discussed such as immediate bottom line results, reduced outage costs, less downtime, good customer relationships and increased overall revenues to utility, improved and effective maintenance, pinpointing the fault location, reduced operational costs, reduced power losses in system[ii]. It can help avoiding the duration and frequency of outages, along with detecting the quality of material, work performed as well as rectifying bad work practices [iii]. The causes of abnormal temperature detected by thermal means help to increase the life cycle of the equipment along with avoiding any other related hazard [iv].

In this paper, different image processing techniques have been discussed to augment thermography process of substation which are based on different kinds of algorithms for automatically and speedily locate the faults and hotspots. All these techniques are refining the results of thermographic inspections. Multiple technology trends of thermography like Robotics inspection, HD thermal detectors, efficient fault detection algorithms, pulse and modulation thermography are being implemented in the diverse fields like power systems, substations, detecting faults in pipe lines, wood deformations, concrete defects, inspection of machineries, corrosion monitoring, welding process inspection, bruise detection in fruits etc. due to its usefulness of applications in different fields.

II. Background of Infrared Thermography Instruments

The infrared (IR) radiations were discovered by William Hershel during his experiment which revealed that the some of the radiations refracted from the prism onto thermometers showed high temperatures which for first time showed that there are some forms of energy which are invisible to human [vi]. The concept of thermal imaging can be made clearer by understanding the concept of the black body radiation. The term black body was introduced by Gustav Kirchhoff in 1960. The black body radiation is an electromagnetic radiation for a material that is thermal equilibrium with the surrounding environment. The type of radiations emitted by the materials can be considered as the black body radiation. The radiations emitted by a perfect black body lies in the infrared spectrum which is not visible to the human eye as it is not sensitive to observe such low wavelengths. The black body absorbs all the radiations thrown at it and also has an emissivity of one. The black body has a frequency spectrum depending upon the temperature of the body known as Plank's Spectrum or Plank's Law [vii].

$$M_{\lambda}(\lambda,T)=\frac{c_1}{\lambda^5}\frac{1}{e^{\frac{c_2}{\lambda T}}-1} \quad (1)$$

where M (W/m^2) is spectral radiant exitance, λ (m) is wavelength of radiation, T (K) is absolute temperature of body , c_1 and c_2 are the first and second radiation constants respectively.The interpretation of the formula produces a series of curves corresponding to various temperatures. The exitance is zero near λ=0 and increases to a maximum value at λ_{max} and then again becomes zero at higher wavelengths. As the temperature of the black body keeps on increasing above 500^{o}C, the infrared emissions convert into reddish and radiations appear to the human eye in the visible spectrum. By differentiating Plank's law with reference to λ to find maxima, we get Wien's Displacement Law[viii].

$$\lambda_{max}=b/T \quad (2)$$

where T (K) is absolute temperature and b is the constant of proportionality and is called Wien's Displacement constant having value equal to 2898x10^{-6} which explains the fact why colors change from red to orange as with increase of temperature. By further integrating the Plank's law from λ=0 to λ=infinity, we get Stefan-Boltzmann's Law, which is given as[ix]:

$$W=\sigma T^4 \quad (3)$$

where W (W/m^2) is spectral intensity, T (K) is absolute temperature; σ is Stefan-Boltzmann constant of proportionality. From this law, one can determine the power radiated from anybody in terms of its temperature.

A. *Thermal Radiation Principles*

In real word applications, no material perfectly behaves as a black body which has property to exhibit perfect emissivity. There are three parameters for real world materials when radiation energy impinges on it: a fraction of it is absorbed α, some of it is reflected γ and remaining of it is transmitted τ. From these parameters, a law named Total Radiation Law is derived which is given by formula[x]:

$$W=\alpha W+\gamma W+\tau W \quad (4)$$

On further simplification, the formula is reduced to following form:

$$1=\alpha+\gamma+\tau \quad (5)$$

These parameters absorption coefficient (α), reflection coefficient (γ) and transmission coefficient (τ) depend upon the material properties and may have a value anywhere between zero and one. Another important parameter encountered while making thermal inspection is emissivity (ε) which is the property of the material to radiate the amount the energy which is absorbed by it. In general terms, the spectral emissivity is the ratio of radiant energy emitted from the material to that of a perfect black body at same temperature and wavelength conditions.

B. *Instruments for Temperature Detection*

Different Types of equipments are employed to measure the temperature of materials. These instruments are: glass thermometer, thermocouple, resistance temperature detector (RTD), thermistor, pyrometer, infrared thermography. Only infrared thermography will be discussed here.

1) *Infrared Thermography*

The thermographic inspections work on principles of detection of infrared radiations and convert these radiations into a visible thermal image. The radiations measured through the lens of thermographic devices are in fact coming from different sources which are to be interpreted correctly. In infrared thermography system, two kinds of infrared detectors are used to detect the radiations in infrared spectrum i.e. mid wave (MW) and long wave (LW) having measuring ranges of 2–5 µm and 8–14 µm of the electromagnetic spectrum band, respectively[xi]. It is interesting to note that these detectors are not designed to detect very low range infrared waves in electromagnetic spectrum because of the effect of atmosphere to infrared radiations, there are uncertainties introduced in the measurements due to cause of blocking of some of radiations by atmosphere [xii].There are two kinds of thermographic instruments being used for condition monitoring:

1. Infrared thermometer (thermographic gun)

2. Infrared camera (focal plane area)

The infrared thermometer has a serious drawback that it focuses at only one point at a given surface area and provides temperature reading of that point and it is prone to missing the hotspots that exist. Some thermal line detectors are also there which have a somewhat better field of view coving a larger area. On the other hand, with the recent advancement in technology, electronics laced thermographic camera has revolutionized the field of thermography. It provides more flexibility and accurate results although cost is downside of it [xiii]. The specifications of the infrared thermographic camera FLIR T440 is described in Table I as:

TABLE I
TECHNICAL DATASHEET OF FLIR T 440

Sr. No.	Features	Details
1	Temperature Range	-20 ºC to 1200 ºC
2	Zoom	8X continuous
3	Multi spectral Dynamic imaging	IR image with enhance detail presentation
4	Frame Rate	60 Hz
5	Field of view (FOV)	25"x 19"
6	Focus	Manual/automatic
7	Thermal sensitivity (N.E.T.D)	<0.045 ºC at 30 ºC
8	Detector Type	320x 240 pixels
9	Spectral Range	7.5 µm to 13 µm
10	Image modes	Thermal/visual
11	Lens	25º
12	Measurement Range	40m to 200m

III. THERMOGRAPHY IN ELECTRICAL SUBSTATION

The application of thermography in electrical substation brings vital importance for the effective maintenance of substation. In this section, measurement approaches in thermography, type of faults in substation equipment, the constraints in thermal inspections and finally thermal image processing techniques will be discussed.

A. Measurements Approach

There are two criteria defined for deciding the level of criticality so that necessary maintenance action may be performed.

1. Quantitative Approach
2. Qualitative Approach

In quantitative measurement [xiv], the exact temperature of the point of interest is taken for evaluation. The quantitative measurements require accurate data extraction methods because of lot of variable factors to be accounted for during thermographic inspection. The Fig.1 shows an example of quantitative approach of thermography in which abnormal condition of 220kV current transformer is diagnosed.

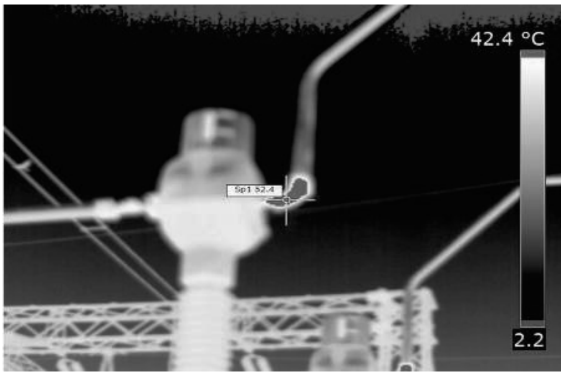


Fig. 1: Quantitative thermographic diagnostic approach

The Fig.1 above shows that the current transformer with abnormal heating pattern. Because of various external factors influencing the quantitative measurements, the exact temperature obtained through thermal imaging means is error prone thus the image has to be processed and accurate results have to be calculated based on the extrapolation methods. The quantitative approach for fault diagnosis is tabulated in Table II.

TABLE II
QUANTITATIVE APPROACH OF FAULT DIAGNOSIS

Sr. No.	Temperature of Equipment	Severity level of fault	Remarks
1	Temp. >130 ºC	Serious	Emergent shutdown of equipment for necessary repair and maintenance.
2	100ºC≤Temp. ≤130ºC	Mild	Perform repair and maintenance as soon as possible.
3	75ºC≤Temp. Rise<100ºC	Incipient	Monitor continuously until possible

The Fig. 2 shows an example of qualitative thermography [xv] which is more robust technique in a way that different components of same nature in a similar environment are compared with each other to find any problems. In qualitative approach, the difference of temperature (ΔT) between the similar phases is used for fault analysis. It is also known as comparative thermographic technique.

Fig. 2: Qualitative Approach of Fault Diagnosis

Here, one can observe that three phases of 220kV isolators are investigated in a single field of view to diagnose any anomalies present. It is clear from above figure that the red phase (farther) down the picture has an absolute temperature of 62.1 ºC as compared to other two phases, yellow and blue, having almost similar temperatures. Thus it indicates clear fault in red phase. This thermal view explains the importance of qualitative measurements and its easy apprehension. Now the fault must be attended in accordance to some criteria to perform necessary maintenance activity without any loss of equipment or productivity. Therefore, qualitative approach of fault diagnosis is tabulated below in table 3, which is divided into four categories according to condition of equipment and a priority is devised to investigate the fault [xvi]. This method is also called **ΔT** method [xvii].

TABLE III
QUALITATIVE APPROACH OF FAULT DIAGNOSIS

Sr. No.	Temperature Rise (ΔT)		Remarks
	Over Similar Phases	Over Ambient	
1	ΔT >15ºC	ΔT >40ºC	Indicates Major discrepancy which should be attended immediately
2	-------	20ºC≤ ΔT <40ºC	Monitor continuously until corrective measures can be taken
3	4ºC≤ ΔT <15ºC	11ºC≤ ΔT <20ºC	Indicates possible deficiency which must be attended during planned shutdowns
4	1ºC≤ ΔT <4ºC	0ºC≤ ΔT <10ºC	Indicates probable deficiency which warrants investigation

B. Thermographic Inspection of Joints

During the thermographic inspection, most of the problems that are encountered are at the joints. The joints are where two similar or dissimilar materials are connected together are usually the weakest link in the product design so a special attention is to provided to assure that joint is strongly bonded and has a life time of product. Infrared thermography technique can be applied to monitor different types of bonds which are mechanical linked joints, welded joints and adhesively bonded joints [xviii]. All the connecting surfaces are rough on micro scale, in fact the coupling between the two solid surfaces is where the roughness of one surface meets the roughness of the micro peaks of the other mating surface so in actual the contact area is very little. The corrosion and oxidation are responsible for the connector degradation [xix]. During the initial stages of degradation the coolness of the surface might not be detected through thermography. The inspection not only helps in rooting out defects but also helps in detecting design defects and its operation in a certain environment. Hence a technique has been suggested by author where a computerized model is used to describe the relation between temperature of electrical connection and surface temperature to find accurate results. A general rule of thumb is during thermographic inspection the load current should be more than 30% as load less than this leads to inaccurate results [xx]. The electrical anomalies found at the contact junctions having equation of equilibrium of contact junctions[xxi] which is as follows:

$$0.24.I^2.(R_k\text{-}R_l) = \alpha_{ef}\,(T_k\text{-}T_l).\,F_k \qquad (6)$$

Where
I = Electric current in the busbar, A;
R_k, R_l = Contact resistance and resistance of bus bar (without contact), Ω;
T_k, T_l = Temperature of contact & the Busbar, K;
F_k = Square of contact radiating surface, m^2;
α_{ef} = Radiation intensity of contact & bus surface ,W/m^2.

The infrared thermography has redefined the criteria of maintenance. Instead of performing preventive maintenance on the equipments, the utilities are urged to perform predictive maintenance courtesy of infrared thermography. The equipment maintenance is prioritized based on the permissible temperature limits. The author experience shows that most of the hotspots are due to the bolted connections and isolator contacts deformation with time [xiv]. The measurements taken in a substation are prone to variable loading conditions, so in order to estimate an accurate result of the inspection even at loads less than 30%, a method has been proposed by Tommie M. Lindquist [xxii] to determine the probability of time to failure of a large number of electrical contacts in a substation. The Fig. 3 shows some of the measurements of thermographic inspection in which problems are encountered in joints at substation.

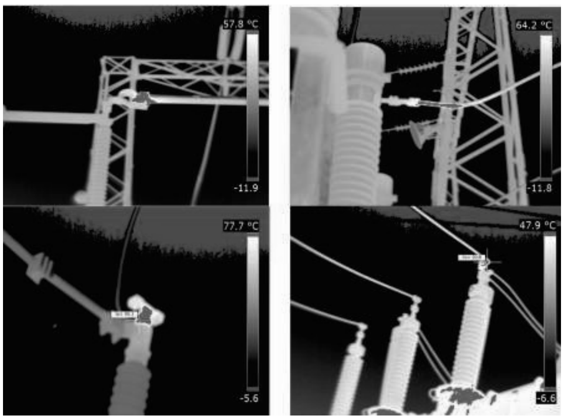


Fig. 3: Thermal analysis of electrical joints in substation

The temperature rise at the joints calculated for different loading conditions is equated as[xxiii]:

$$T_r = T_m (I_n/I_{load})^2 \quad (7)$$

where T_r=temperature rise, K;

T_m=temperature measured, K;

I_n=nominal load, A;

I_{load}= load current, A.

A probability density function is mapped to determine the rate of failures and maintenance programs for the suspicious contacts. As more measurements over the years are performed the overall results accuracy is increased.

C. In Sight and Out of Sight Faults

Infrared thermography helps in monitoring the electrical stresses on the substation equipments due to which timely preventive intervention could be made to avoid system failures. During diagnosis of high voltage equipments with faults, it was found there were two types of faults;

(i) External faults
(ii) Internal faults

The external faults are simpler to interpret but it takes some going to extrapolate the causes of internal faults in the equipments[xxiv]. The loose connection of circuit breaker contacts, current transformer contacts, inferior insulation of CCVT, low oil in Current transformer, ingress of moisture in the surge arrester, leading to breakdown of these high voltage equipments, are some examples of faults discovered during thermographic inspection. The external faults are shown in Fig. 4.

Fig. 4: Thermal View of Internal Inspection of Substation equipments

D. Anomalies in Power Substation Equipments

There are different types of equipments employed in substation for controlling, voltage regulation and protection of power system. As these are in large number employed in a large substation, it requires their proper maintenance plan and equipments knowledge. The thermographers must have knowledge about the component identification and thermal signatures to be obtained from different substation equipments. Different components behavior must be thoroughly studied like power transformers, instrument transformers, surge arresters, insulators, on load tap changer before inspecting these equipments [i]. The faults in a substation can be classified into loose connections, open or short circuit, overload, unbalanced load and improper component installation [iii]. The poor connections are base of faults most of the time [ii]. The different anomalies occurred in a power substation equipments are given below:

1) Transformer

The following types of faults can occur in transformer.

Oxidation in contacts, loose and deteriorated connection, load unbalancing, blocked or chocked radiator tubes, overloading, poor ground connection, unleveling of transformer tank, unbalanced load, low level of oil.

2) Circuit Breaker, Disconnector, Lightening Arrester, Cables

The following types of faults can occur in above mentioned.

Poor electrical connection, oxidation in contacts, misaligned breaker and isolator contacts, overheated lightening arrester, overloading, Failure of metal oxide discs of lightening arrester, improper connection at splices of cables, insulation breakdown in cables.

3) Bus Bar, Capacitor Banks, Fuses

The faults are: Overloading conditions, poor electrical connections, overloading conditions, corrosion.

4) Motor and Generator

The faults are: Blocked Rotor, harmonics, poor connections of connectors, poor heat dissipation, slip rings and commutators overheating.

E. External Factors affecting thermal inspections

There are some constraints regarding the thermography which should be addressed to obtain error free results. These factors if neglected can cause influence during IR inspections in an air insulated substation (AIS) and consequently leading to erroneous condition evaluation of the equipment under analysis. Since this research is based on air insulated substations, so the stress has been on these factors. Such factors of influence can be characterized as procedural, technical or environmental factors [xxv] which will be discussed one by one.

1) Emissivity

During the thermographic inspection, one of most important factors to be counted for, to make accurate readings, is emissivity of materials to be inspected. Actually the readings recorded by the thermal means fall in the infra red region in the electromagnetic spectrum where the luminance have maximum value. The emissivity is the ability of a body to emit the infra red radiations. The black body is ideal with respect to emitting the absorbed energy. For a black body the emissivity is one but emissivity of electrical equipments varies between the vales of 0.1 to 0.95 depending upon material characteristics. As the thermographic camera measures the surface temperature of the objects so if emissivity factor is not correctly compensated, wrong temperature readings would be recorded as the temperature measured would not account for the reflections as well as refractions which would compromise the inspection process [xxvi]. Another important consideration during thermal inspection of substation is the angle of view. The angle of view of measurement also affects the emissivity values because the apparent temperature depends upon the angle of view along with thermal camera field of view. Thus these important facts must be taken into account[xxvii]. The emissivity of various materials are given in Table IV below[xxviii-xxix].

TABLE IV
EMISSIVITY OF SOME COMMON MATERIALS

Sr. No.	Description of Material	Temperature °C	Emissivity
1	Aluminum anodized	70	0.97
2	Aluminum weathered	17	0.87
3	Asphalt	4	0.96
4	Asbestos	20	0.96
5	Brass oxidized	100	0.61
6	Brick	20	0.93
7	Bronze powder	25	0.78
8	Carbon graphite	20	0.98
9	Clay	70	0.91
10	Concrete rough	17	0.97
11	Copper oxidized	20	0.88
12	Fiber board	20	0.85
13	Gold polished	100	0.02
14	Iron cast	1000	0.95
15	Lead oxidized	200	0.63
16	Magnesium	538	0.18
17	Nichrome oxidized	500	0.98
18	Nickel oxidized	1227	0.85
19	Paint different colors	70	0.93
20	Paper black dull	20	0.94
21	Plastic glass fiber	70	0.94
22	Platinum	538	0.12
23	Rubber	20	0.95
24	Sand	20	0.90
25	Skin human	32	0.98
26	Water ice	0	0.97

2) Reflected apparent temperature

When inspecting substation components, there may be other sources of radiation between thermal imaging device and electrical equipment. If the emissivity is low and there is any other source reflecting, then this factor must be adjusted for correct measurements.

3) Humidity

The rain, fog or snow may cause cooling and mask incipient faults in electrical equipments during inspection. Any potential faulty point may be cooled to temperature where it seems to be normal. Thus humidity factor must be fed to device to get accurate results. However for short distances, the humidity factor does not appreciably affect the measurements.

4) Distance/Object size

Another factor is the distance to the equipment from the inspection point. If distance to object is very large object is too small, then error is introduced which must be accounted for. This factor if neglected can take the priority into serious nature so it is imperative proper attention is made.

5) Wind

The wind at the outdoor substations has a significant impact on the thermographic inspections as it produces a reduction in the temperature effect as given by equation:

$$F_R = 1 - k.(1-e^{-v/V}) \quad (8)$$

where k and V are the coefficients which depend upon the equipment and v (km/hr) is the velocity of wind [xxx]. As wind affects the temperature significantly and the substations are located all over the world having variable wind velocities throughout the year, so some correction factor must be applied to get accurate measurements. This correction factor at different wind speeds has been calculated experimentally and is tabulated in Table V below:

TABLE V
CORRECTION FACTOR FOR WIND SPEEDS

Wind Speed (m/s)	Wind Speed (knots)	Correction factor
1	2	1
2	4	1.36
3	6	1.64
4	8	1.86
5	10	2.06
6	12	2.23
7	14	2.40
8	16	2.54

6) Solar Irradiation

Solar heating raises the temperature of the equipments above the ambient temperature so a reference temperature must be calculated to negate the effect of sun's heating and used in measurement process.

F. Significance of Image Processing Techniques

As discussed above, numerous factors affect the measurements, so images obtained after the inspections are in raw form which may be erroneous so if action proposed to be taken according to non-dependable measurements could result in a significant revenue loss to a utility due to wrong interpretations. Most of the IR camera also has software applications, so that after capturing thermal images, they can be further analyzed. But the analysis requires qualified personnel having experience in the field of thermal inspection and along with that it is time consuming. Hence automated techniques are proposed to expedite the process and analysis of thermal images to minimize the operator dependence thereby enhancing the reliability of thermographic inspection. Generally in the image processing initially the thermal image is preprocessed, after that it is segmented from the background, then feature extraction algorithm is applied to extract the requisite features from the image, then image is classified for decision making

Different approaches or methods have been proposed earlier to investigate the faults through image processing means and they will be discussed in the following.

An automatic diagnostic method based on infrared thermography has been proposed using the statistical method based image processing and morphological processed image techniques, also collectively give rise to infrared thermography anomaly detection algorithm (ITADA) [xvii], are utilized to detect the presence of any problems in the system. In order to expedite the process of thermography, this algorithm is used to perform inspection effectively and accurately countering the effects of human errors during inspection. In this technique, the image is separated from the background using Otsu's statistical threshold selection algorithm [xxxi] and then morphological means are used to extract the hotspot in the image.

The thresh holding image obtained A (x,y) from the original image B (x,y) is defined as:

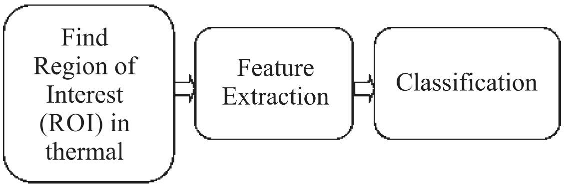
$$A(x,y) = \begin{cases} 1 \text{ if } B(x,y) > T \\ 0 \text{ if } B(x,y) \leq T \end{cases} \quad (9)$$

Where T is thresh holding value obtained by Otsu method. In order to determine the reference temperature, the average grey value of the picture other than the hotspot point will be computed. Then the hotspot temperature will be compared with the reference value computed.

In another technique, instead of using grey level images, the original image is processed. Only the points around the fault will be extracted while the non-relevant points are set to zero. In this method Zernike Moment is used to find feature vector and all those non-faulty points will be flushed out in this phase. After that the image is classified by designing image classifiers such as Support Vector Machine (SVM) [xxxii]. SVM uses the kernel to convert the feature vectors into high dimensional feature space in linear form. Surge arresters are important equipment for safety of power system to divert the surges safely to ground. A new image processing method, Watershed Transform, has been applied to segment the thermal image accurately. Then the computational results are used to train a neuro-fuzzy logic networks having three layer topology by using the thermographic results databases having hundreds of points of interest [xxxiii]. The results of digital signal processing and neuro-fuzzy networks have been validated to be within 10% to classify the operational performance of arresters as faulty, normal, light and suspicious.

The original RBG data is captured by the help of thermographic camera and it is a straight forward image processing method in which pixel region tool for the target image is derived [xxxiv]. The information deduced is then used to train a three layer artificial neural network (ANN) using Levenberg Marquardt algorithm. This method has a major drawback that the processing time is very high being calculated by ANN. A software based program, SIDAT also called integrated system for automatic diagnosis, has been proposed for automatic fault diagnosis of transformer which includes infrared thermography, Chromatography, Chemical and Electrical Tests to confirm the operation of power transformers. It is based on Finite State Machines (FSMs) which takes into account the above testing procedures to describe the time life of transformer to analyze accordingly. In this module, thermography has been designed to substitute the high cost thermovision cameras as all the processing is performed by the thermography module. Hence it is clear that thermography has evolved one of the dependent technologies to count on for maintaining the substation [xxxv].

A new fault diagnosis method is suggested to root out the electrical problems. There are in general a total of four steps in sequence for the thermal image processing:



The above hierarchy has been utilized by the author by using K means algorithm as feature extraction process by dividing the thermal image into five clusters and applied SVM (parameter optimization) as the classifier to final optimal final result. Thus a better and accurate result has been obtained for automatic fault detection [xxxvi]. This technique is shown in the Fig.5 whereby original images are shown and the resultant clustered images are shown in Fig. 6.

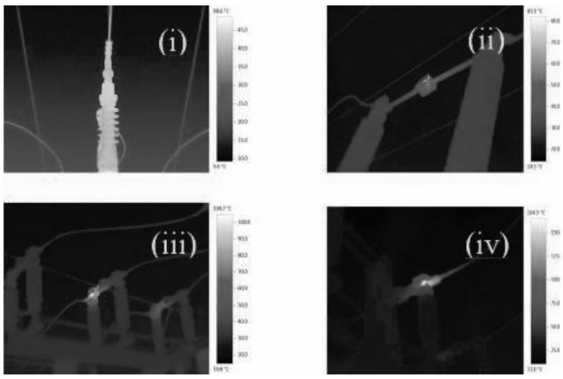


Fig. 5: Original infrared images, from left to right are (i) normal (ii) general failure (iii) serious failure (iv) emergency breakdown.

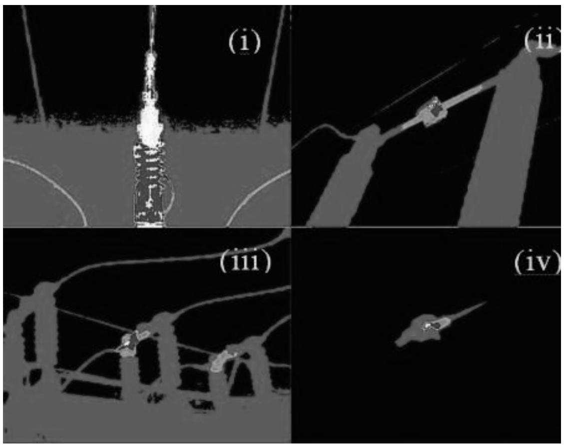


Fig. 6: Cluster results, from left to right are (i) normal (ii) general failure (iii) serious failure (iv) emergency breakdown.

The transmission lines faults can be effectively diagnosed with the help of thermal image processing. As transmission lines are prone to fault due to the environmental factors, early fault detection is the key for maintaining the reliability. Due to the exposedness of the transmission line system to the environmental impacts the thermography is a key predictive maintenance tool for the proper operation of power systems.

The infrared thermography has been applied for fast detection of the transmission lines automatically through preprocessing the thermal image by converting the RGB image into grey level histogram to enhance the contrast and eliminate noise. Then cellular automation is then applied to segment the preprocessed image. After that, the transmission line is detected using Hessian matrix, then temperature information is used to find the fault if temperature is above threshold value. This method has an accuracy of above 90% to detect power transmission lines faults accurately [xxxvii]. The below Fig. 7 illustrate this process.

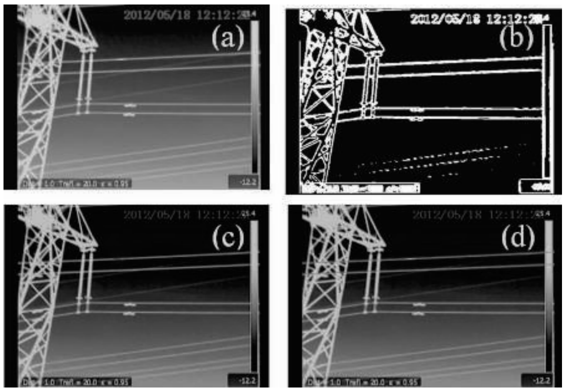


Fig. 7: (a) Grey scale image (b) Segmented image (c) Detection of T/Line (d) Detection of Hotspot (From left to right)

1) Thresholding Technique

In Image processing thresholding technique is very accepted way of automatically detecting the hotspots [xxxviii]. This technique is commonly used to extract the target image from the background [xxxix]. If only one value is used as thresholding value, then it is known as global thresholding and technique involves segmenting sub-images inside target image, it is called local threshold. In that regard, some thresholding techniques have been discussed here.

a) OTSU Thresholding Technique

In this technique, it involves finding the optimal thresholding value by discriminant criterion. It maximizes the between class scatter by minimizing sum of within class variants of foreground and background pixels. This is excellent method to apply if number of pixels are likely similar to one another [xxxi].

b) *Kapor Thresholding Technique*
Another technique for thermal image processing has been proposed in which the image foreground and background are considered as two separate class signal sources whose entropies have been summed to obtain maximum entropy image. From this thresh holding value T is obtained called Kapur Thresh holding Technique [xl].

c) *Hamadani Thresholding Technique*
In this technique, the first order statistical features have been utilized to find the hot region in the target image[xli].

d) *Kittler and Illingworth Thresholding Technique*
In this technique, the pixel classification error rate is optimized based on minimum error thresholding (MET) algorithm [xlii].

e) *Iterative Thresholding Algorithm*
Iterative thresholding algorithm is suitable application for IR images where image does not provide deep valley histogram to segment the image. Thus an arbitrary threshold value is chosen and image is segmented into foreground and background. A new threshold value is calculated from the average pixel intensities and then new and old threshold values are iteratively compared with each other unless a minimum is found[xliii].

In the preceding section, different techniques have been presented to segment the images such as thresholding, clustering based, boundary/ edge based, active contour based. All these techniques are based on the quantitative measurements of pixel intensity. However in electrical equipments, load imbalance or fault in only one phase could occur, so qualitative measurement is always preferred approach. In this method , the image segmentation is done by local key point detection which results in better performance with respect to find Region of Interest (ROI)[xliv].

A new method namely recursively constructed fuzzy systems (RCFS) is presented to determine the electrical faults in equipments. This method automatically realizes the hotspots by recursive application of proposed algorithm. This method has sets the priority levels, normal, warning and critical to establish the maintenance program [xlv]. In another approach, the thermal images are automatically identified by another technique based on Maximally stable extremal region (MSER) algorithm to find out the region of interest. To find similar equipment within the thermal image, Euclidean Distance method is used. The similar equipments are then grouped together for segmentation process then by using qualitative approach , the thermal faults are accurately calculated [xlvi].

In another fault detection technique, two systems Non-invasive Off line Visual Inspection system (NIOLVIS) and Non-invasive Real Time Visual Monitoring system (NIRTVMS) have been proposed. The images obtained through thermographic inspection are segmented color wise to detect the hot regions in the image, features are extracted and matched. Afterwards, an algorithm based on redness of region is applied to find out the severity of problem to generate the tripping, alarming and controlling signals. This method of diagnosis presented is robust in the presence of humid, extreme hot and cold temperature variations [xlvii]. Another Image processing tool namely Region growing method has been effectively used for the segmentation of IR image. In this technique, some seed point is selected and region around the seed point grows according to some predetermined criteria like pixel intensity. If the intensity falls comparable to seed point then region grows. This method has a key advantage that it does not cause over-segmentation of the image thus the accuracy is better[xlviii].

Another infrared software tool based on MATLAB is presented where the thermal measurements are taken without direct comparison method as it suffers from different external factors. In fact same objected when inspected at different times may yield different thermal trends as accurate qualitative analysis results are quite challenging [xx]. The Invariant coefficient method is used to find the hotspots. The thermal ratios defined in test object are determined which represents a robust model with respect to load variations and external factors. The similar components temperature ratios in an object need to close to one under normal conditions while the other component ratios need to be normalized. In another method, instead of using the conventional grey level histograms, the thermal images of electrical equipments are converted to HSI (hue, saturation and intensity) color model for processing. Then edge detection technique is used for finding hotspots in thermal image[xlix].

The high voltage substation risk assessment has been evaluated by thermographic inspection by using neuro fuzzy controller [l]. The approach is used to determine the urgency of intervention for maintenance decision. The age, voltage level, temperature of hotspots, DGA result, Dielectric breakdown strength of oil etc. are fed to the fuzzy controller to be used in risk maps for appropriate decision making. This helps in maintaining the system as the decision is based on the many different input parameters on which system is being operated.

The above mentioned techniques of image processing for automatically finding hotspots are summarized in the form of table which shows what hotspot detection technique as well as fault classification tool are being applied for the operation and maintenance of power system.

TABLE VI
AUTOMATIC DIAGNOSTIC TECHNIQUES FOR HOTSPOT DETECTION

Sr. No.	Authors	Hotspot Detection Technique & Fault Classification Method
1	Y.-C. Chou and L. Yao	OTSU thresholding method and morphological image processing technique [xvii]
2	A. Rahmani, J. Haddadnia, and O. Seryasat	Zernike Moment and SVM method [xxxii]
3	C. A. L. Almeida, A. P. Braga, S. Nascimento, V. Paiva, H. J. Martins, R. Torres, *et al.*	Watershed Transform and Neuro Fuzzy Logic [xxxiii]
4	M. A. Shafi and N. Hamzah	RGB value comparison and Artificial Neural Network (ANN) [xxxiv]
5	A. M. Carneiro, A. Pasquali, M. E. R. Romero, E. M. Martins, R. Santos, J. M. Silva Filho, *et al.*	SIDAT based on Finite State Machines (FSMs) [xxxv]
6	Z. Hui and H. Fuzhen	K means algorithm and SVM image classification [xxxvi]
7	S. He, D. Yang, W. Li, Y. Xia, and Y. Tang	Grey level histogram threholding and Hessian matrix to detect transmission line [xxxvii]
8	M. M. Ahmed, A. Huda, and N. A. M. Isa,	Recursively constructed Fuzzy systems (RCFS) [xlv]
9	M. S. Jadin, S. Kabir, and S. Taib	Maximally stable extremal region (MSER) and Eucladian Distance [xlvi]
10	Z. A. Jaffery and A. K. Dubey	Colour Wise segmentation and Algorithm based on redness of region of interest [xlvii]
11	Z. Korendo and M. Florkowski	Invariant Coefficient Method [xx]
12	M. Žarković and Z. Stojković	ANN based fuzzy controller [l]

G. *Robotized Inspection of Power Lines*

To further automate the process of thermography, robots have been utilized for on-line monitoring of the power transmission lines. The fault in power transmission lines can be automatically diagnosed using thermovision technique carried out via robot due to this; the human errors are rectified as process is automated. The image extracted by robotic mounted thermographic camera, acting as a server, after capturing the images in resolution of 320x240 sends the packets of raw data to client image processing software, where the image is processed to extract hotspots from power cable [li]. In another robotic thermographic inspection, the thermal camera records a stream of video and then sends data to the software which process the images for fault detection. The real time monitoring of power system utilizing thermography reaps high benefits for early fault detection in transmission lines[lii].

H. *Economic Aspect of Thermal Inspections*

One thing should be kept in mind the conventional thermographic approach will require experienced personals to carry out detail inspections and root out the external problems which are visible as well as internal equipment problems which are invisible which requires experienced and skilled personnel. The costs due to external inspections will be high keeping in view the contracted staff, more detailed inspections as equipment depreciates with the time requiring more expenditure eventually if analyzed over the life time of equipment, the cost related to these inspections come out as high running costs overall. In a method proposed by author known as internal inspection, the MATLAB Based GUI program is developed having a database of all the equipment on the plant, the personnel dealing with the software will have easy method to apply thermographic process automatically with overall less cost. The overall time in evaluating the fault analysis will be quite reduced by the software. The cost saved by internal inspection is about 6.3% with reference to external inspection process which could save a significant amount of capital to the owner[liii].

I. *Applications of Infrared thermography*

There are many applications of infrared thermography in different fields of life some overview of these applications will be discussed here.

The presence of leakage currents on the structure of power transformer causes localized overheating on the screws of the transformer which bind the upper cover and body together. This overheating is detected by thermographic camera. These stray eddy currents can tear of the paint on the body, cause the gas kits to soften up contaminating the oil and also ultimately be a cause of major failure. The author proposed a solution to this problem by installing a copper sill around the screws to provide a bridge to the stray fields directly to the earth and also greater surface for heat dissipation thus reducing the temperature of the hotspots on the screws thus enhancing the life of transformer[liv].

The electrical and thermal characteristics of Metal oxide varister (MOV) under power frequency have been discussed where the thermal runaway property of MOV is related to its maximum temperature limit. The surge arrester leakage current consists of two components, from which resistive current is main indicator of the healthy condition of metal oxide surge arrester. As the resistive current increases due to any defect, the heat generation becomes more than the heat dissipation that's the point where surge arrester becomes thermally unstable. With the help of thermography on can predict the leakage current of varister by the image processing of the thermal image extracted thus keeping a close watch on the performance of varister [lv]. In another study on the surge arresters, a series of experiments conducted on surge arresters due to its operation in variable external environmental factors like variable wind, humidity, reflected temperature, increased voltages than rated to determine the relation of change of resistive current and the temperature of surge arrester during all the set experiments was determined by thermography to relate the effect of leakage current with the results of thermography thus to improve the validity of thermal inspections. The thermographic parameters needed to be tuned keeping in view these variable external effects [lvi].

As all the substations or plants contain the panels for the wiring for control, protection, regulation, indications, metering and various other purposes, the proper maintenance of these panels is important to keep the availability of substation or plant. The thermographic monitoring technique is quite successful in maintaining these panels. The qualitative approach is applied to probe any anomalies in the panels thus increasing the efficiency, life time of panel equipments [lvii]. The induction motors are important equipment in the industrial environment. A new intelligent method has been proposed for condition monitoring of three phase induction motor. The color based segmentation technique is used to determine the hot regions in the motor along with red color intensity algorithm to find and declare the healthiness of motor [lviii].

One of the important applications of thermography is in the field of PV systems. As demand for clean energy is growing day by day, a need has arisen how to maintain these panels efficiently and effectively It helps to determine the defects of the PV panels so it helps in the detection of defects even during the production stage thus avoiding losses to production company. It helps in identifying mismatched cells, bypassed diodes fault, high resistance soldering joints, packing material degradation and resistive shunts in the PV panels. All these defects give rise to hotpots which is readily detected by thermal imaging thus enhancing the overall efficiency of PV systems [lix]. Aerial solar thermography is used to find the condition of the solar panels in the large arrays of solar (PV) power plant. As a damaged cell in a panel not only causes the electrical output to reduce but if that damage cell persists over longer periods of time it also spread the damaging effect to the cells around it and eventually the panel becomes unserviceable hence in that regard solar thermography has been very useful for proper maintenance of solar panels [lx]. In another research, the PV array consisting of series and parallel combination of panels diagnosed for faults using thermography to find maximum power point tracking to examine the problem of partial shading condition. If against such problem is not acted upon, then along with reduced output power , hotspot occur producing maximum power points (MPPs) which can affect the neighboring cells in the PV array producing increased losses. The PV panels with complete faulty rows, mixed and healthy cells were thermally inspected to find global maximum power point (GMPP) of the PV array by comparing their power output[lxi]. The Fig. 8 shows short circuited PV module[lix].

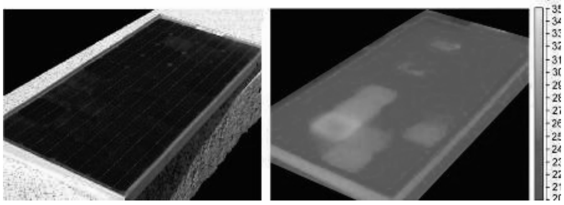


Fig. 8: (a) photovoltaic modules; (b) IR image of module short-circuited under fine weather in outdoor conditions.

Thermal imaging application in food industry has revolutionized the conservation and quality of food. Due to its non-invasive analytical nature of measurement than the contact type thermometers and thermocouples, the scope of food safety, pasteurization, sterilization, cooking has reached new levels. The drying of foods for long period of conservation is now more quality oriented by its application by modeling the dehydration kinetics thus the determining final drying temperature and to develop the efficient control system. The products can be verified for standard packing by monitoring the ingress of bad contaminated air or in other words the whole packing methods can be verified[lxii].The Fig. 9 shows the difference of temperature between sound and defected tissues in apple[lxiii].

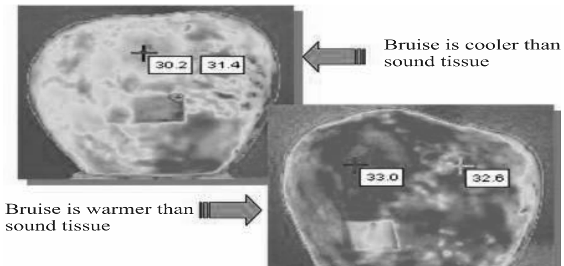


Fig. 9: Temperature variation for bruise tissue and sound tissues in red

The application of thermography in the field of art work has enabled to detect any sub-surface level defects with the help of determining the temperature distribution across the art work. The non-contact type appliance is required to investigate the problems hence thermography fits the requirement. The method of non-destructive heating to the specimen is applied which is used to determine the temperature signals based on the uniformity of the model by creating a test duration and optimum sampling interval [lxiv].The Fig. 10 shows the application of thermography in art works[lxv].

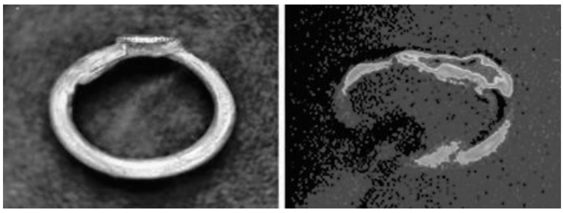


Fig.10: (a) Photograph (b thermogram of a Phoenicians ring revealing the material used to weld the collet to the support.

Wood is material used in all forms of buildings and materials. The preservation of wood is vital for long endurance. Thermography is utilized to inspect the decay detection of wood. Firstly, with the varied levels of moisture content, the thermal inspection is performed and found out the moisture level is in direct relation to temperature difference. Then the defects with varied depthless has been inspected to determine the problems and found out that as depth increases the temperature difference decreases but still it is possible to get a sniff about the defect for long duration inspections[lxvi].

In inspecting the welded joints, the joints where two similar or dissimilar materials are connected together are usually the weakest link in the product design so a special attention is to be provided to assure that joint is strongly bonded and has a life time of product. Infrared thermography technique has been applied to monitor different types of bonds which are mechanical linked joints, welded joints and adhesively bonded joints. The pulse and modulation thermography techniques have been deployed to check the bond between surfaces. The later technique was particularly stressed because of less variation due to non-uniform surface heating and emissivity factor[lxvii].The Fig. 11 shows the defects in wood detected by IRT[lxviii].

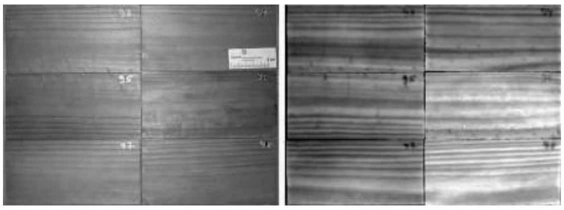


Fig. 11:The photo (left) shows a small wood panel and the thermographic image (right) the compressed wood as white (hot) area within the material.

The ball bearings are used within every rotational machines and it is imperative to inspect the condition of ball bearing as it has a direct impact on rotational performance of machines. The machine with little loss of lubricating oil showed increased levels of temperature as compared to normal due to higher force of friction. Also by vibration spectral analysis, the results were confirmed but it has a disadvantage that it is contact type method so extra experimental arrangements have to be made. The damaged, loss and normal samples have been segregated[lxix].

The pipelines are being used in many industrial as well as power sectors. The defects in the pipe line affect the performance of the system. With the help of thermography, both the internal as well as external defects of pipe line heat insulation layer (PHIL) can be probed into non-intrusively. The maximum temperature can be determined and the depth and dimensions of the leakage can also be analyzed comprehensively so as to conserve the system operation[lxx].

IV. Challenges and Future Scope

It has been clear that the thermography has emerged to be one of the effective diagnostic tools in different fields of the world as explained in the preceding sections. Like any other field, the research in this field also requires constant up gradation and improvement with the passage of time. One of the improvements needed in the electrical substation thermography is to carry out the inspections of unmanned substations through robots with real time image processing capabilities. This can be achieved with artificial intelligence based programming to automatically adapt to the system loading conditions and make appropriate measurements and decisions accordingly with varying loading conditions. In such cases the decisions will be very important regarding the system stability as less loading conditions up to 30% do not reveal right results by the existing thermographic methods.

One of the much needed improvements can be to integrate the thermography with the Substation Automation system (SAS) to speedily discover any anomalies in the substations. This can be achieved by implementing robotic based continuous surveillance of substation equipment. Additionally, such surveillance efficiency and reliability can be further enhanced by deploying fast fault classification methods having redundant combination of Artificial Neural Networks (ANN) and support Vector Machine (SVM) to feed their combined results to SAS system which can help in improving the reliability of the substation system and overall power system. Also The economy is also a major constraint especially for third world countries to implement thermographic based fault detection techniques, this field must be globally invested in by manufacturers to help the performance of power systems.

V. CONCLUSION

Infrared thermography has emerged as one the excellent condition monitoring technique which helps in on line monitoring of a process and non-intrusive way of inspection. It helps in predicting the faults thus preventing breakdowns or catastrophes at a later stage thus reducing the maintenance costs and down time consequently resulting in massive savings both from the operational point of view as well as asset safety. The inspection of electrical installations by infrared thermography poses challenges due to non-homogeneity of the thermal images extracted. Thus, the augmentation of image processing tools has revitalized the field of thermography as the thermal images are automatically investigated by fault detection algorithms. The image processing methods also have eliminated the possibility of most likely human errors, the external environmental impacts and other noise signals to provide an accurate results of analysis of thermal images thus a lot of savings could be effected that would have to be invested in outsourcing the substation inspection to experts. Due to the diversified nature of thermography technology, it has applications not only in field electrical substation and power system but also wood inspection, PV systems, food industry, pipelines, art works and other fields as briefly reviewed in this paper. These different applications of thermography as reviewed in this paper can be quite helpful for successfully implementing and producing the desired results in temperature measurement and heat signature based processes.

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