Thermography-based diagnostics of power equipment

Infrared analysis tools and an algorithm to assess the condition of power equipment are demonstrated. Thermographic analysis capabilities and limitations are highlighted, and then the dedicated software toolbox is presented with its features overview. Finally an approach to infrared measurements trending for use in condition monitoring applications is demonstrated. Feasibility of the proposed solution is verified with a case study of an HV disconnector inspection.

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Reliable and uninterrupted operation of transmission and distribution equipment poses a key challenge in the area of monitoring and maintenance of power engineering systems. The most desirable diagnostic practice today is early detection of potential defect locations that allows for scheduling preventive actions before the major failure occurs. Thermovision is a tool that has gained a good reputation in the field of HV/MV systems inspection and is widely used in diagnostic engineering practice worldwide as a part of preventive maintenance programmes. The principal advantage offered by thermovision is that it is a non-contact and non-destructive technique, well suited to monitoring devices operating under high voltage or carrying high current.

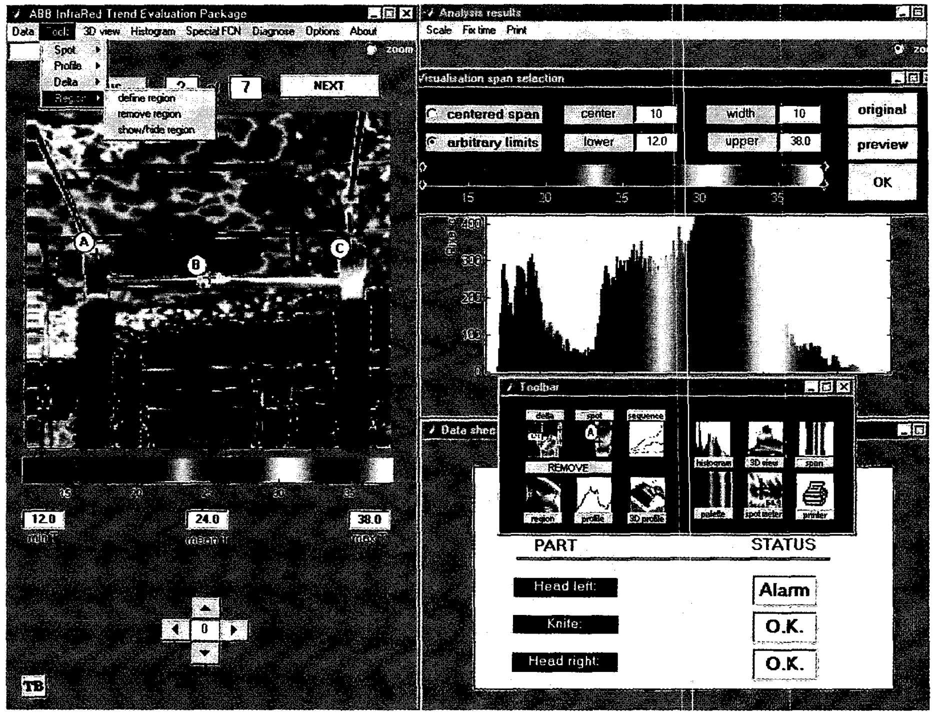
Typically the technique is meant for processing single-shot measurements. A substantial problem arises though when it comes to analysis of a sequence of thermograms collected at different time intervals, say, every three months. The actual bottleneck in carrying out such an analysis lies in load variations over time (hence heat production), and external measurement conditions (e.g. ambient temperature) and repeatability of the camera position with respect to the object in question (i.e. framing).

To perform thermographic trend analysis of electrical equipment a software toolbox, under the name IR-TEP (InfraRed Trend Evaluation Package), has been designed and developed at ABB Corporate Research in Cracow, Poland. IR-TEP covers the needs of processing thermographic sequences and provides algorithms for thermographic trend analysis. The tools were developed to support ABB service units in their maintenance activities in the power transmission and distribution segment.

In recent years, due to rapid technology and hardware development (advanced cameras, new detector technologies, progress in cooling systems), infrared thermography (IRT) has delivered more value than any other electrical preventive maintenance inspection technique (see for overview References 1 and 9, and also References 6-8).

Thermal images are pictures of heat rather than light. The measurement principle is based on the fact that any physical object radiates energy at infrared wavelengths (i.e. within the IR portion of the electromagnetic spectrum). Thermal cameras can measure and visualise emitted infrared radiation evoked, for example, by current flow as is the case with electrical devices. Surface temperature distribution is thus recorded in the form of a thermogram. Note that the ability to radiate heat is a material property (called *emissivity*) and so some materials (e.g. aluminium) may radiate little energy despite their high surface temperature because their emissivity is low.

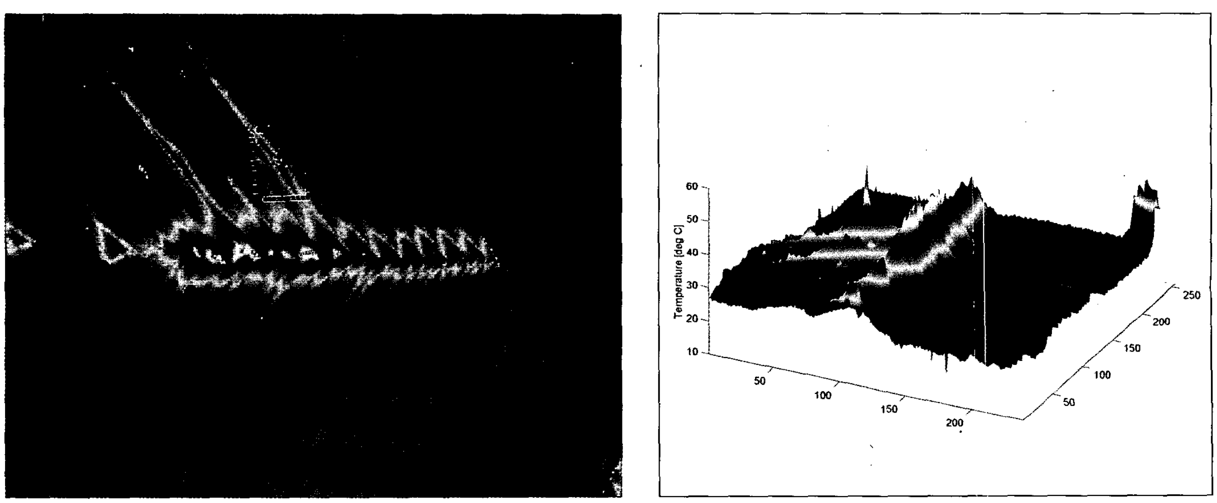
1 IR-TEP software package – general view

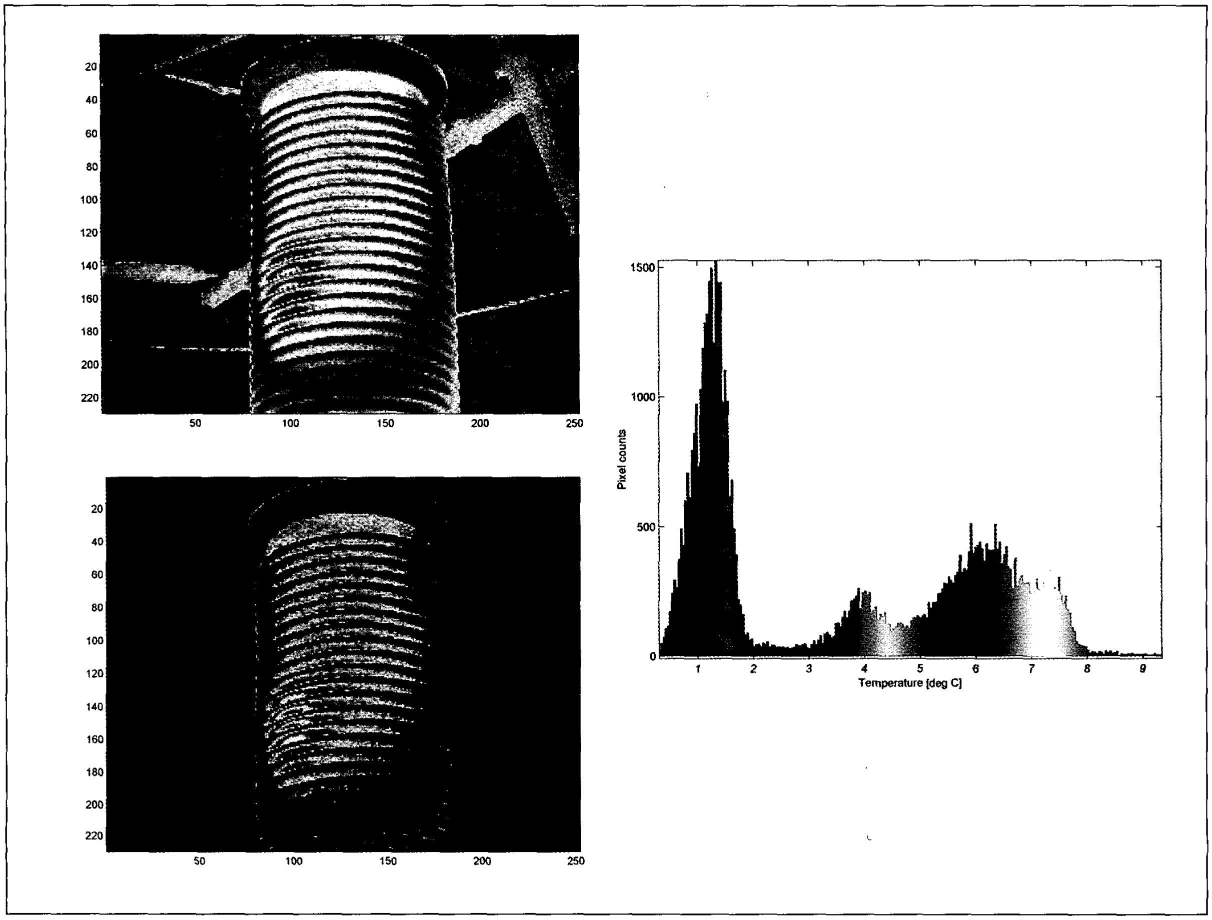


The most common thermography-based diagnostic technique allows for in-service condition assessment, but without reference to past measurements. The current state of an object is evaluated from single or multiple thermograms of the area in question taken, however, at the same time.[3,7] A widely used method in thermographic condition assessment is to consider the temperature difference (delta) between the problem area and the corresponding area on another identically loaded object or its part (assumed to be in the correct state) as a reference. This procedure is commonly used for electrical three-phase devices.[2]

The heat generation process in electrical devices arises due to resistance changes or current (load) increase (according to the $P = I^2R$ relation). Just as informative are situations when there is no heat dissipated, contrary to expectation, which may suggest a circuit break. Such a situation, though, usually becomes apparent before in-the-field inspection is carried out.

2 Thermogram visualisation in 3D





3 Histogram and image thresholding

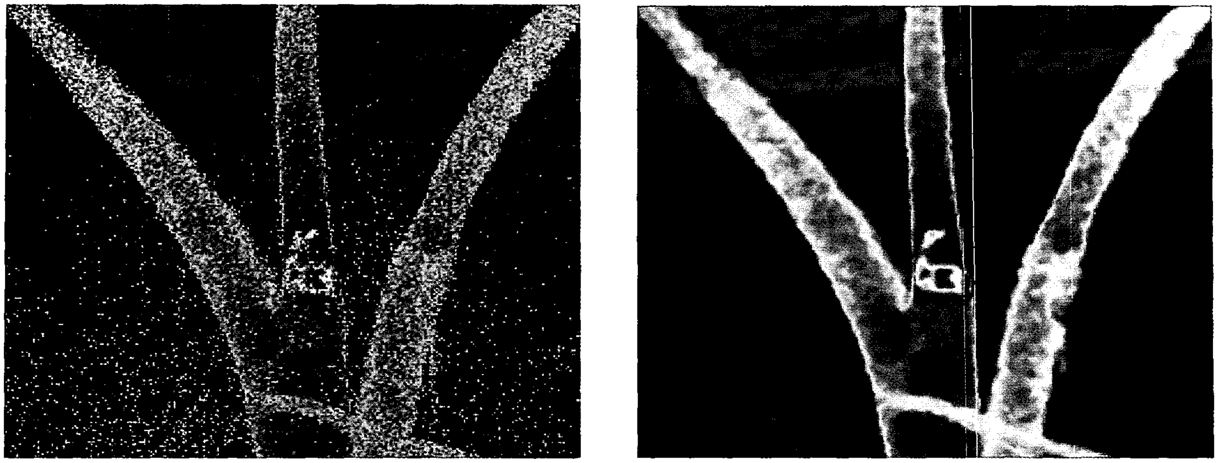
There are numerous defects that become apparent in infrared well before they become critical. The most common are: bad contacts (loose, corroded cable connections, defective sliding or tulip contact etc.), inductive heating (bolted connections), current leakage, inter-winding short circuits, clogged transformer radiators, tap changer malfunction, winding condition in instrument transformers, and many other.[1,2] A precondition to study any of these defects with IRT is to operate the object at minimum 30-40% of the rated load.[10]

Technical and business benefits

Infrared thermography is often referred to as a preventive, as well as a predictive, maintenance tool. In general it is then extremely hard to provide an accurate evaluation of potential savings made possible by application of IRT. The main reason for this is that the IR technique helps avoid occurrence of major failures by detecting possible failure development areas (thus shifting from the 'upon-failure' maintenance to proactive maintenance), so the actual prevented failure impact is rather hard to predict, and its cost range could be easily underestimated. In fact, what we are trying to measure are the costs we have avoided thanks to the unscheduled downtime we have eliminated or the equipment pieces that have not blown up. Still, it is possible to establish the major factors influencing the overall maintenance costs and reveal attainable savings with the application of IRT.

IRT brings benefits from a number of business-oriented areas, including cost-effective weak point localisation without downtime and improvements in plant availability, reliability and operational safety. Also IRT gives clues for ranking the equipment condition and the resulting actions (retrofit or replacement) and better control over maintenance services and spare parts stock (see Reference 9 for an overview).

Another important advantage is the possibility to validate computer simulations with



4 Filtering-out measurement noise with a lowpass filter

IRT, which gives feedback for new product development.

Design goal and assumptions

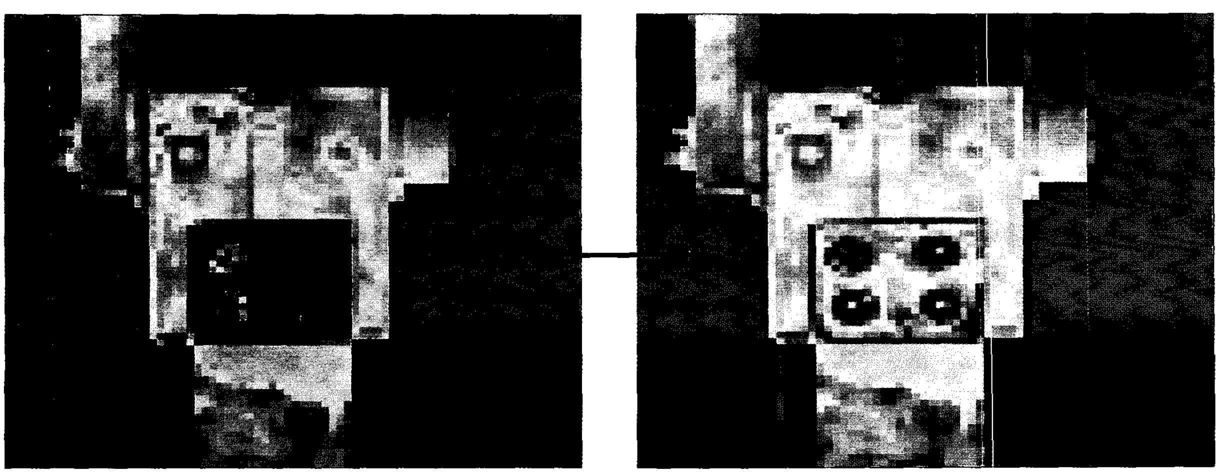
The principal objective was to develop an approach to circumvent the inherent thermal picture dependence on changes in load and external conditions. This becomes an issue particularly for thermal trend analysis where establishment of a common reference level is of the primary importance. Due to its different operational and constructional individual properties, each distinguished object features certain potential problem areas that should be first taken under a 'magnifying glass' when performing the thermal trend analysis. To localise such areas a statistical analysis was carried out on numerous equipment samples and a relevant thermographic database was set up.

All thermographic measurements were performed with the use of Inframetrics IR camera model PM280E. The in-the-field inspection data were collected at a number of locations including industrial and state-run (electrical utilities) substations. At all times current load and ambient conditions were noted. Most measurements were made at early morning hours to eliminate the sun pre-heating influence.

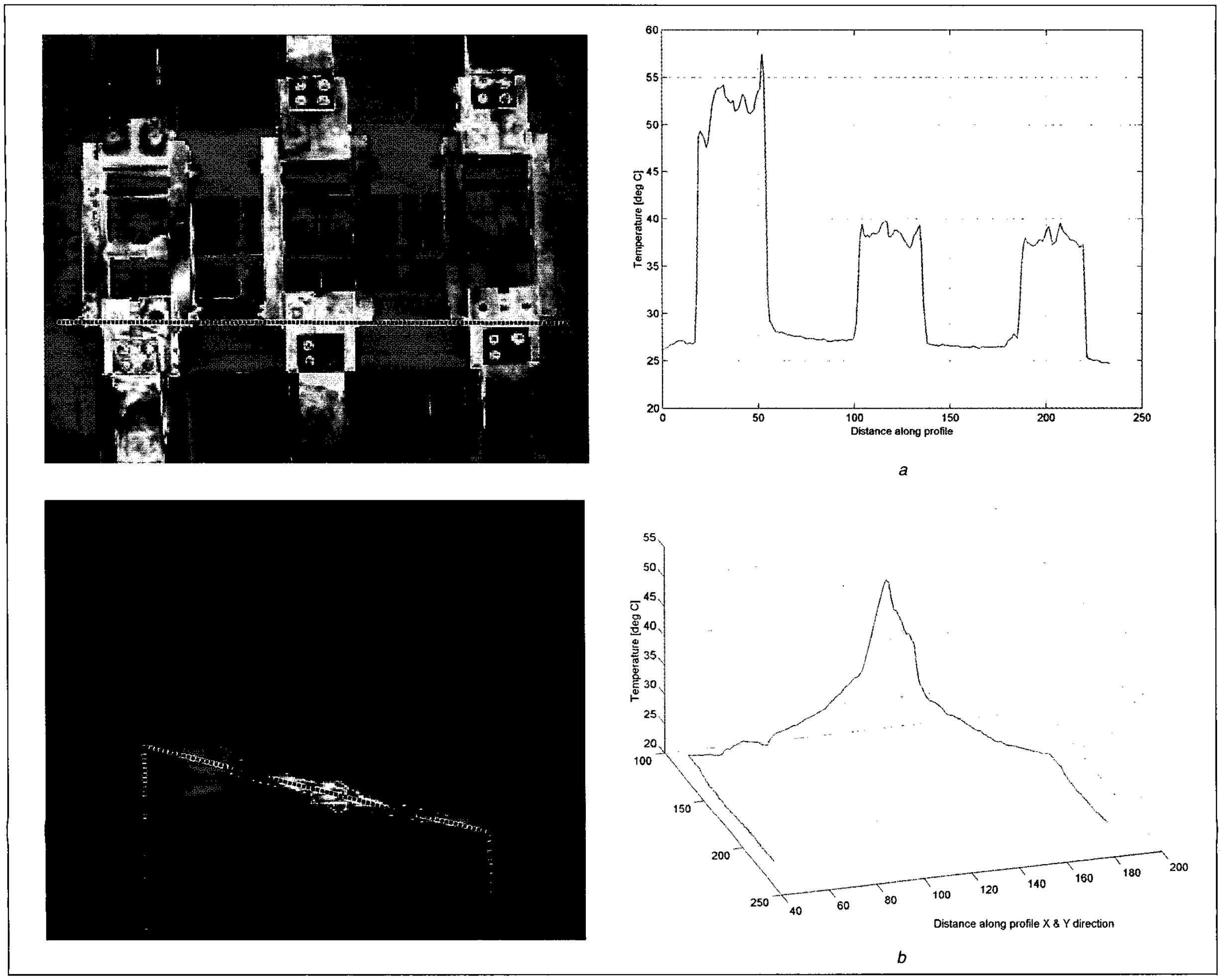
The proposed solution allows for thermal trend analysis without direct temperature comparisons. The definition of thermal invariant factors makes the state assessment robust to changes in the operating and ambient conditions. A set of logic rules provides a reasoning engine to assess the condition, localise the defect and assess the future development.

Hardware and software tools

The development platform was the Matlab software that is commonly used within the engineering community. The choice was driven



5 Local emissivity adjustments



6 Temperature profiles – 2D and 3D

by versatile image visualisation and processing capabilities of Matlab that can be easily integrated with a number of other functions in the frame of available Matlab toolboxes and enhanced further by the programmer.

IR-TEP does not require the thermographer to possess broad technical background nor needs to be skilled in Matlab software itself. The user interface was developed with Matlab-based graphical user interface (GUI) tools. It is based on a pull-down menu-driven command set. The workspace is organised in three panels. Apart from the main control window the two others serve purpose of analysis results display and auxiliary data display, respectively (Fig. 1).

A number of image-related data are displayed once an image is loaded: the file name, minimum, maximum, mean temperatures and a colour bar with corresponding temperature colour mapping. Any of the information displayed (thermogram, histogram or profiles) can be conveniently zoomed-in and out with a mouse.

The IR-TEP package supports thermographic data in either Inframetrics TIF, AGEMA IMG or in the Matlab data MAT file format. The latter option allows for loading thermographic sequences along with any changes introduced in the post-processing phase like local emissivity corrections, image shifting (object re-framing) or ambient temperature settings.

An image sequence is composed of a number of preloaded thermograms of the same object taken at different times, suitable for trending. Each time an image is loaded the corresponding measurement time is recorded (with resolution down to seconds if needed) to ensure proper time-scaling.

A thermogram is nothing but a matrix of temperature data, each element of which corresponds to one pixel size area on the object's surface. The standard approach in the thermographic analysis is to visualise the temperature distribution with a set of colours (colour map) assigned to temperature values over a selected range. IR-TEP offers a variety of tools supporting data visualisation. A number of colour maps allow for tailoring to specific requirements. The display can be fixed to span colours from minimum to maximum temperatures over the whole sequence; thus the same colours stand for identical temperatures in each consecutive thermogram. To focus on details, one may want to choose the colour to span over a temperature range within a selected region or any arbitrary range.

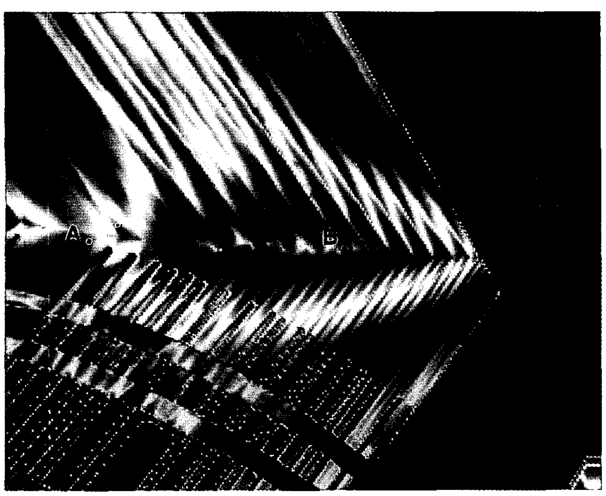
In many cases the increased temperature field is so small (e.g. due to object's geometry) that it may easily be overlooked on a regular 2D image. The 3D thermogram representation (Fig. 2) reveals such cases as peaks protruding above the surface. Here not only is colour used for temperature coding but also protrusion height.

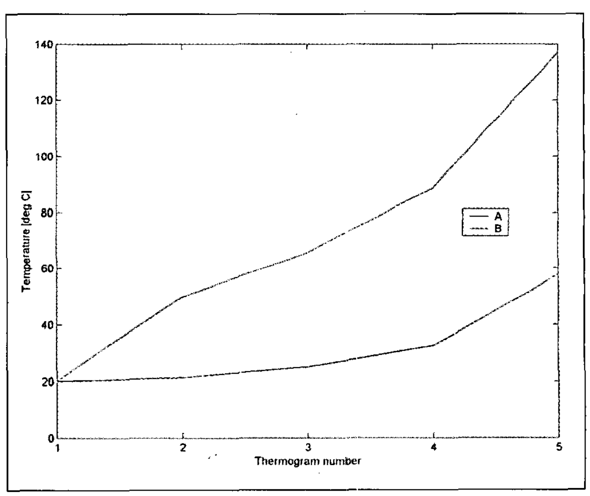
Sometimes it is useful to discard cooler background details or investigate an object located nearby a far hotter one. By manipulating the visualisation span one can threshold the temperature data to focus on the issues of interest (Fig.3). The threshold level can be easily read out from a built-in IR-TEP colour-histogram function that can be obtained for the whole image or any sub-region selected. The temperature bins are not only distinguished by appropriate values denoted on the x-axis, but also the colour coding is retained (this way one can look-up the threshold temperature level corresponding, for example, to all areas in violet and blue).

In certain cases the camera is over-sensitive for the given application and so the temperature quantisation is too fine. The thermal image then reveals too many details that are irrelevant to the problem under examination. Applying 2D low-pass filters helps to focus on the essential temperature variations on the level corresponding well with the analysed phenomenon (Fig. 4). A wide range of standard smoothing filters is built-in in IR-TEP, including averaging, median, Wiener and gaussian filters. Additionally one may wish to extract individual part contours with edge filters: Laplace, Sobel or LoG or enhance contrast by histogram equalisation or a dedicated contrast filter. Should the built-in filters set not meet some specific needs there is the possibility of applying the 2D convolution with any arbitrary convolution kernel tailored to the required frequency response of the filter.

The problem of proper data interpretation arises from the fact that usually industrial devices are composed of many components featuring different surface characteristics (material, coating, finish etc.) that yield emissivity differences, whereas in common measurement practice one sets the emissivity to be equal to one for each image pixel. This way two elements of exactly the same temperature may appear substantially different on an infrared image. To correct this misleading situation local emissivity adjustments are necessary, and they can be introduced with IR-TEP (Fig. 5). For a thermal sequence recorded with the fixed camera position with respect to the object one can define a mask of emissivity corrections that will be applied to all thermograms within the sequence.

7 Spot trend – pointwise temperature change over time





A valuable insight can be gained from investigation of the temperature distribution (profile) along a given line segment or broken line specified (Fig. 6*a*). This feature can be set to display data also in 3D (Fig. 6*b*) with the third dimension (height) corresponding to the temperature value.

The IR-TEP design target was to provide tools allowing the performance of the analysis in the time domain also. This can be achieved in two modes: pointwise and profilewise. In the first mode one can set up to six points whose position with respect to the image co-ordinates will be fixed across the sequence (i.e. common for all thermograms). If the images are properly ordered in the sequence (monotonically in time), with the corresponding temperature values at each specified spot, the temperature trend as a function of time can be plotted (Fig. 7). One has to remember though that these readings are not compensated for the environmental and operating conditions that may differ from one measurement instant to another.

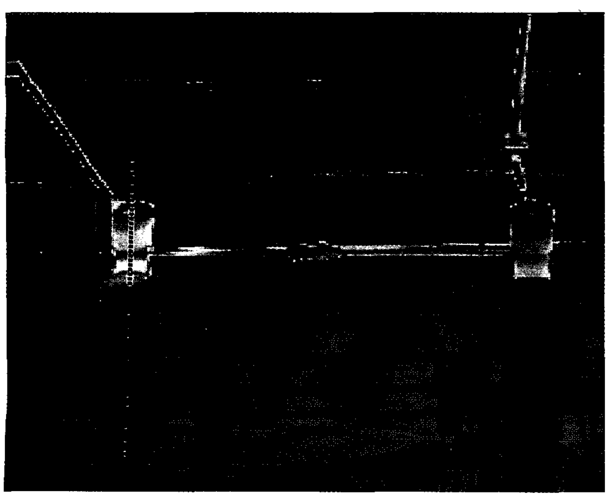
The program retrieves each measurement time automatically (at file download) with the resolution down to seconds; thus relevant time scaling is possible depending on the nature of the actual experiment. For example the factory heating test of a power transformer core produces a sequence spanned over four hours, whereas a disconnector state monitoring may take months between consecutive shots.

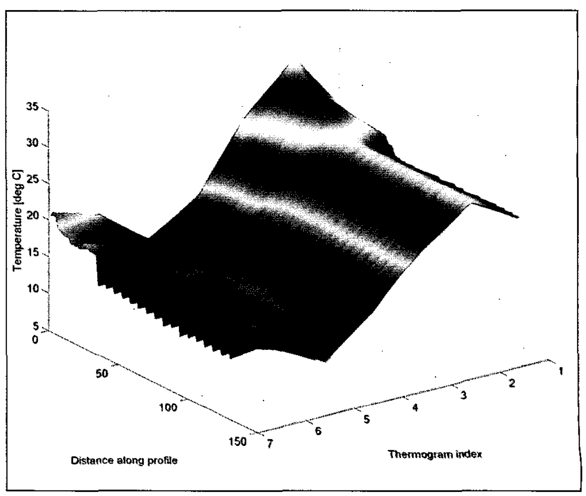
Similarly it is possible to define a line segment and plot the temperature profile evolution over time as a 3D mesh plot (Fig. 8). Because it is impossible to guarantee the identical camera position from measurement to measurement, a line segment or a spot that is common for the sequence might not hit exactly the same component on each thermogram (e.g. the background instead of the cable terminal). To overcome this difficulty IR-TEP is equipped with a tool to shift each image independently in any of four perpendicular directions, if necessary, to get approximate overlapping.

Finally the most advanced IR-TEP feature allows for load and environment-independent thermographic trend evaluation. The thermophysical properties differ from one object to another, so the analysis algorithms must be insensitive to these factors to detect faults properly. The development provides a tool for dedicated trend analysis tool (patent pending) for HV/MV disconnector as the most common location of defects among the substation equipment suitable for thermographic diagnosis.[6]

Thermographic sequence analysis

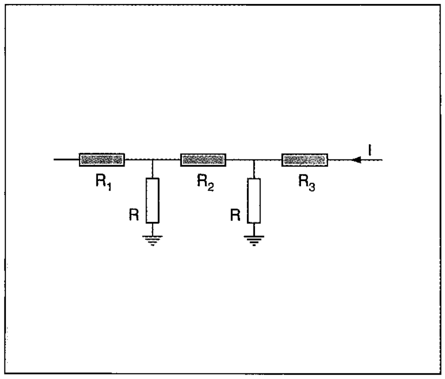
Typically in common thermographic practice the current state is evaluated from single or multiple thermograms of the object in question taken at a certain time. The surface temperature, as measured by the camera, reflects not only the object's internal condition but just as much the operating conditions (i.e. current load) and environment: sun irradiation, air temperature, wind-forced cooling etc. This is due to the fact that the actual surface temperature distribution is considerably affected by a number of factors unrelated to any defect development. Consequently, a direct temperature comparison between thermograms of the same object, but taken at different operating conditions, is not correct. In fact an object with





8 Profile trend – temperature profile change over time

9 Electrical circuit equivalent model of heat flow in a swing-arm disconnector

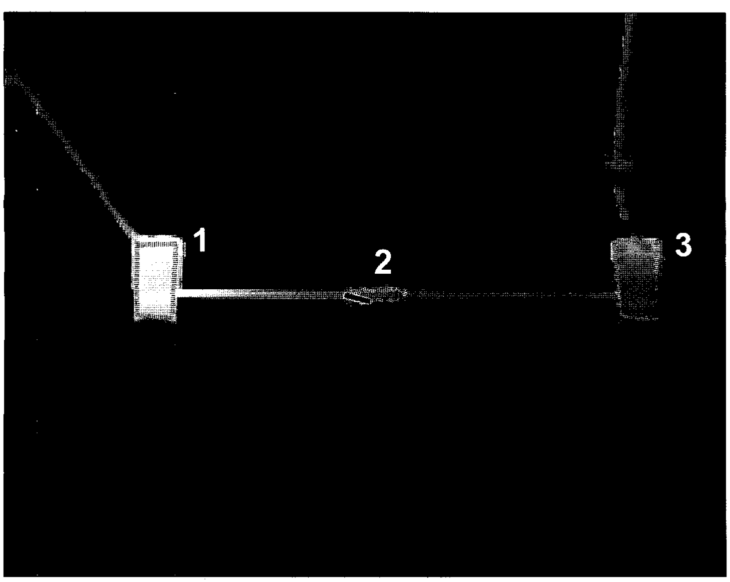


no developing defect may yield very different camera readings when inspected at different times. Some authors propose analytical or experimental methods to compensate for, for example, load variations, yet these solutions may not be general enough.[2,4,5] On the other hand many of these factors (e.g. wind) are not quantifiable to the extent allowing for straightforward analytical compensation.

Another technical problem with processing of thermal sequences is variable camera positioning during off-hand in-the-field measurements. Even minor differences in the viewing angle with respect to the inspected object yield different object framing (shifted, rotated) thus making pixel-to-pixel automatic comparison (e.g. subtraction) impossible. The proposed way to circumvent this is to pre-select the target regions thereby disregarding their actual position in the consecutive frames.

The qualitative analysis of thermographic images of electrical equipment is a highly challenging issue in general and only few authors report successful in-the-field implementation.[7,8]

10 Critical subregions definition



Invariant coefficients method

Nearly all HV/MV disconnector failures are located at either the heads (cable terminals) or the connector zone. It seems fully justified then to focus on these areas to pinpoint a possible developing defect.

The proposed solution exploits the fact that, as a disconnector construction features full symmetry, its thermal behaviour should follow a similar pattern.[8] Due to basic electrical laws the same current flows along the whole path, including the heads and disconnector arms. In its correct state both heads should yield the same surface temperature distribution and any load-dependent internal heat production variations should result in similar thermal responses unless the electrical resistance changes, which would indicate a defect. The same applies to varying ambient conditions as both parts are subjected to the very same ambient conditions. It is proposed then to consider mutual relations between the predefined 'problem areas' within a given object. In the case of HV/MV disconnectors these are cable terminals and the sliding contact zone.

An electrical circuit analogy is often used in studying thermal behaviour of solid objects because heat resistance and capacity correspond well with their electrical counterparts (i.e. a good current conductor also conducts heat well). For the purpose of thermographic evaluation, it is convenient to assume the electrical circuit representation of a swing-arm disconnector switch (Fig. 9), where resistances R_1, R_3 denote the nominal values of joint resistances of the cable terminals and R_2 stands for the part of the current path that includes the swing arms and the main connector. As the construction of both disconnector heads is supposed to be exactly identical, for the normal condition it holds that $R_1 \approx R_3$ (with accuracy limited by assembly repetitiveness). Resistances R have a very high value and stand for the two supporting columns of the ceramic insulators, through which almost no heat is conducted away.

An incorrect formula, that sometimes can be found in maintenance publications,[10] gives a direct relation between the Joule's law and surface temperature T. It claims T to be directly proportional to the power of resistance heating:

$$T = T_{amb} + cI^2R \tag{1}$$

where c is a constant (kelvin/watt) and T_{amb} is ambient temperature (air). This is contrary to experimental observations[4] and industrial practice, indicating that under typical open-air conditions joint temperature does not rise by as much as the square of the load change.

Basic laws of heat exchange theory give three fundamental mechanisms of heat exchange: conduction, radiation and convection.[12] Because insulators are bad heat conductors and radiation is negligible for temperatures typically observed in electric joints, it is acceptable to assume that in the studied case electrical power is dissipated predominantly by convection. It can be shown that under these assumptions the ratio of temperature delta (ΔT_i denotes a difference between surface T_i and ambient T_{amb} temperature) between the cable terminals and the main connector is invariant to changes in load I and ambient conditions (changed conditions are marked by an asterisk, indexes i, j denote the distinguished disconnector elements: $i,j = 1$ left head, 2 connector, 3 right head):

$$\frac{\Delta T_i}{\Delta T_j} = \frac{\Delta T_i^*}{\Delta T_j^*};\ i,j = 1,\ldots,3 \tag{2}$$

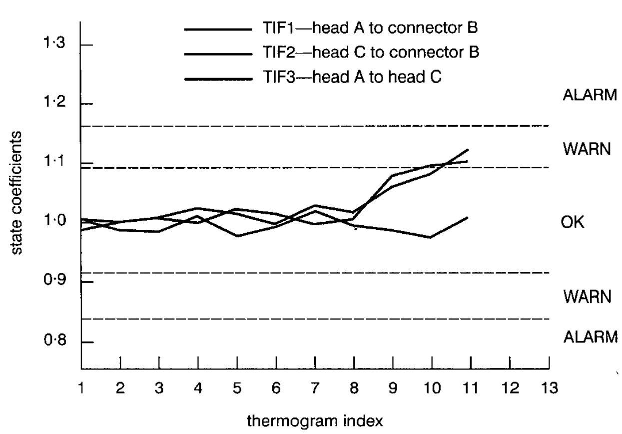
It can be concluded then that the thermal ratios as defined by eqn. 2 change only if any of the joint resistances R_i change, which may be an indicator of a developing fault.

In the discussed approach the thermal ratios are used as factors invariant to load and ambient variations. In the first step a pre-set number of regions is defined. These regions should cover the most critical areas for the given object type. For an HV disconnector these are three characteristic regions (Fig. 10): two heads and the arms sliding contact zone (numbered 1, 2, 3).

Next a characteristic temperature value is computed for all defined regions. In the proposed approach it is taken as a difference between median temperature within each selected area and ambient temperature (median is preferred for its suitability to skip possible outliers, e.g. possible erroneous temperature peaks due to reflections, spots with missing paint revealing bare aluminium). Other methods of computing the characteristic temperatures (e.g. division into subregions and weighted average computation) are also possible and may depend on the actual application. Thereby one obtains three characteristic values ΔT_1, ΔT_2, ΔT_3. Then a set of thermal invariant factors $tif_{a,b,c}$ is defined as ratios:

$$tif_a = \Delta T_1/\Delta T_2;\ tif_b = \Delta T_3/\Delta T_2;\ tif_c = \Delta T_1/\Delta T_3 \tag{3}$$

The above procedure is repeated for all thermograms in the sequence thus producing a train of three-element vectors. In normal condition the tif_c value should be close or equal to one (identical thermal properties), whereas the remaining two ratios need to be normalised



11 Invariant factors trend plot with safety limits

Table 1

Therm. number	1	2	3	4	5	6	7	8	9	10	11
load, A	39	41	45	37	53	44	38	36	47	39	43
	0	5	5	0	0	0	5	5	0	0	0
ambient temperature, °C	14	23	16	18	12	15	20	25	17	23	20

with respect to the first thermogram in the sequence.

The diagnostic reasoning is based on the defined characteristic ratios $tif_{a,b,c}$. Having set arbitrary warning and alarm thresholds that impose a limit on the $tif_{a,b,c}$ variations, we may define a set of *if-then* rules. These rules describe all plausible combinations of $tif_{a,b,c}$ with respect to the thresholds. For example:

IF tif_a > alarm AND tif_c > *alarm*
THEN {region 1 is in *alarm* state} (4)

The resulting conclusions provide one of three possible condition states {*OK*, *warning*, *alarm*} for each defined region. This way we get not only a general state assessment but also information about defect localisation. As we record the findings over time it is possible to extrapolate the $tif_{a,b,c}$ trend lines and assess not only the actual state but also the severity of possible defect development in future.

As an example consider a sequence of 11 thermographic measurements taken on a 110kV/1250A disconnector, operating at a wide range of load and ambient conditions (Table 1). Following the procedure described above a train of the thermal factors $tif_{a,b,c}$ was computed and plotted (Fig. 11). The rule-based reasoning led to the conclusion that clearly there is a problem developing at the left cable terminal 1. Judging from the slope of the increase it will soon shift from *warning* to *alarm* state. Thus an immediate action is required.

Conclusion

This article has presented an algorithm and software package designed for condition evaluation of HV/MV substation equipment with infrared thermography. The tools make it possible to analyse a trend in a sequence of thermographic measurements. Definition of invariant factors makes the algorithm insensitive to changes in load and ambient conditions. The applicability of the proposed approach has been verified with a case study on monitoring an HV disconnector.

More research is needed to investigate values of the severity criteria thresholds used for the condition assessment and how they are related to the actual object type. Also the approach must be tested on devices featuring more complex geometry (e.g. transformers).

Further development perspectives are targeted at enhanced automatic processing capabilities in the form of automatic recognition of the measured object and its critical parts.

Obviously IR-TEP functions can be utilised equally well for other purposes wherever a sequence of thermograms helps gain a deeper insight into the problem.

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