Infrared Diagnosis of Joints in Electrical Power Engineering Using the *RELITE* Method

Ralf-Dieter Rogler

Problem

The defined limit temperatures of electrical power engineering equipment and devices must not be surpassed during the total operating time. During operation, the electrical resistance of the joints is increasing and the joints are ageing. The increasing power dissipation heats the joints more and more. If the equipment is operated for many years without any inspection, the current-floated joints can show temperatures that risk the equipment to fail. The power supply companies, however, want to supply unlimited electrical energy and wish to exclude any undesired breaks of the electrical energy transportation. Therefore, the equipment needs to be inspected periodically, and maintained, if necessary.

The infrared measuring technology enables to measure the temperature rises of the joints without breaking the power supply. The temperature rises of the joints cannot be taken as basis to calculate the resistance and the residual life time unless the environmental influences are taken into consideration, such as the geometry of the joints and the speed of ageing in dependence on the load current.

The usual diagnostic procedure exclusively uses the *joint temperature rise* in order to evaluate the state of electrical joints. This method, however, cannot be used for a long-term status-dependent maintenance strategy.

Solution

The decisive physical *parameter* of a life joint is its temperature, which is determined by the power dissipation as well as the heat transfer and storage capacity of the joint. The joint is *rated* by calculating both the resistance and the residual life time of the joint based on the joint temperature rise.

A proven method to determine the resistance based on the temperature rise of a joint is the thermal mapping of the joint in a thermal network. The analogy between the thermal and the electrical stream field allows to describe the thermal flows in thermal networks consisting of power sources, heat resistances and thermal capacities [1]. The *resistance of the joint* R_J is calculated from both the stream and the distribution of the thermal current and temperatures. The dimensionless relation between the resistance of the joint and the resistance of a conductor of same length is the *performance factor* k_U. This factor is used to describe the status of a joint in general.

From long-term investigations, we know that the ageing of joints in the electrical power engineering is mainly determined by the chemical reactions between the conducting material and the environment [2]. It is possible to describe the chemical reactions using the physical principles, and to extrapolate the course of the performance factor of the joint. This description considers the conducting material, the construction and the current load. When the limit of the performance factor is reached, the joint fails. The residual time from the diagnosis to this failure is called the *residual life time* Δt_R.

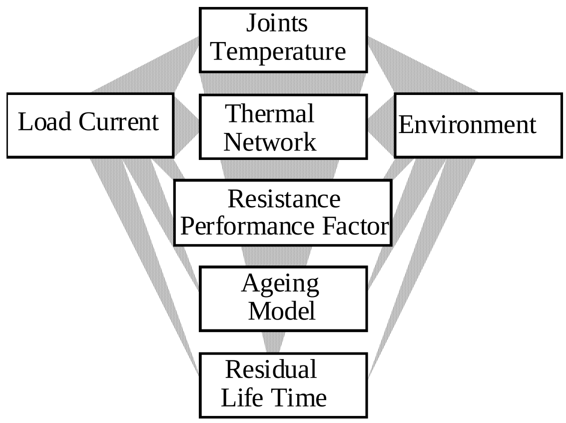

Fig.1. RELITE Diagnosis

Using a thermal network and a chemical ageing model, the residual life time of a

joint can be derived from its temperature rise [3].
This method is called *RELITE (Residual Lifetime)*[*] - (Fig. 1).

Temperature Measurement Using an Infrared Camera

When minimising and compensating the measuring errors of an infrared camera, the temperature rise of a joint can be determined without interferences up to $\Delta\Delta\vartheta_v < 3$ K.

* Measurement in substations and on overhead lines requires a high-resolution infrared camera to be used with a thermal resolution angle of $\alpha_\vartheta < 4.5$ mrad in order to be able to measure the joint temperature with a predefined precision at a distance of **l** ≈ 10 m between camera and joint - (Fig. 2).

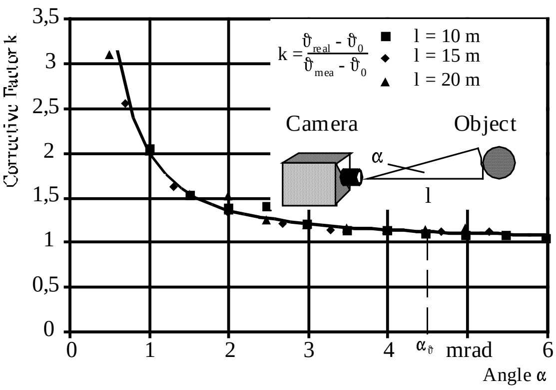

Fig. 2. Thermal Resolution Angle of an IR Camera

* The joint temperature can only be determined if the emissivity ε of the surface of the joint is known. This value can be taken from tables for different materials or from the operating time of the joint for oxidised surfaces made of aluminium or copper [4].

* On the surface of the joint, reflections appear regardless of the value of the emission ε and the value of reflections **r** = 1 - ε. This fact must be considered in order to measure the joint temperature with utmost accuracy. The influence of the reflections in the measured temperature is eliminated within the camera using the emission coefficient ε and the ambient temperature ϑ_0.

* In order to minimise the influence of the ambient atmosphere during temperature measurement, the detectors of the infrared camera measure the received radiation in the infrared windows for wave lengths λ = 2.0 ... 5.6 µm or λ = 8.0 ... 14.0 µm where the atmosphere for distances of less than 10 m is nearly diathermal. The share of sun and sky radiations penetrating the infrared window results in the fact that the camera reports a joint temperature which is actually higher than the real temperature. The measuring error rate of a camera working with short waves is so high that those camera cannot be used in direct sunshine. At cameras working with long waves, the influence of the sun and sky radiation on the measured joint temperature with an emissivity of ε > 0.3 is low because of the clearly larger frequency distance to the sunlight. Therefore, it can be omitted - (Fig. 3).

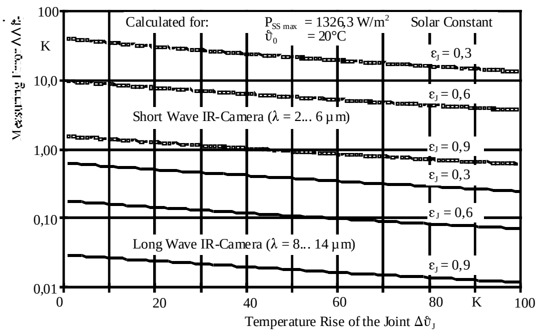

Fig. 3. Measuring Error Depending on Solar Radiation

* If the joint is subjected to a radiation exchange with different ambient thermal objects, then the *equivalent* ambient temperature must be calculated in order to avoid unallowed measuring errors at joint surfaces with low emissivity ε. This is especially valid for diagnoses in open-air locations because the part of the joint which faces the sky will reflect the radiation of the clearly cooler sky. The

---

[*] The method was developed at Dresden University of Technology and the patent is held in Germany under P 44 42 070.6 and in Europe under P 95 11 7985.2.

equivalent ambient temperature ϑ_U results from the ambient temperature ϑ_0, the temperatures of the higher atmospheric layers from ϑ_H = -40 ... 10°C dependent on the amount of cloud b and on that part of the joint surface p_H that reflects the higher atmospheric layers. If the measurement is not executed with the equivalent ambient temperature ϑ_U but with ambient temperature ϑ_0, then the measured temperature of the joint is smaller than the

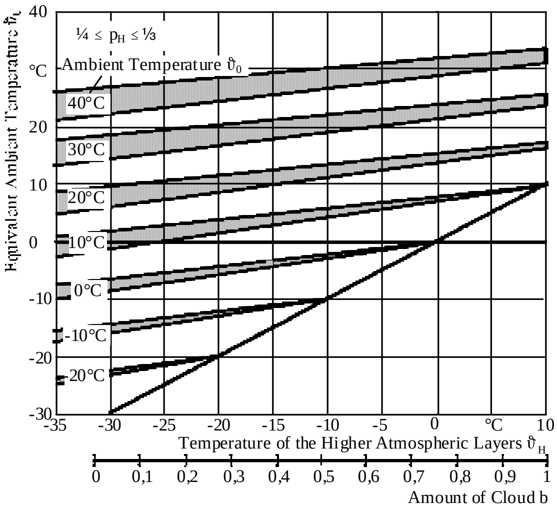

Fig. 4. Equivalent Abient Temperature Depending on the Higher Atmospheric Layers

actual temperature - (Fig. 4) because the higher atmospheric layers are normally cooler than the direct environment.

Determination of Resistances in a Thermal Network

The performance factor of the joint is calculated from the thermal network, independently on the load current, environment and construction of the joint.

* The joint as well as the connected conductors and devices are subdivided into sections for which the following items are calculated: loss of thermal current, performance of the sun and sky radiation, thermal resistance of conductor, radiation, convection and thermal storage capacity.

* The length of the sections with circular diameters of joints and conductors are determined by the radius **r** of the section in question and by the expected axial temperature gradients. The length along the joint and the length of the first section of the line conductor next to the joint amounts to $\mathbf{l_1} \approx \mathbf{r}$. The length of the section $\mathbf{l_n}$ = f(**n**) can be selected variably in line with the increasing distance from the inhomogenity, i.e. from the joint.

* Using the local constant **b** - (Fig. 5), it is decided in how far the conductors and devices connected to the joint must be mapped in order to enable their respective influences on the joint temperature to be considered.

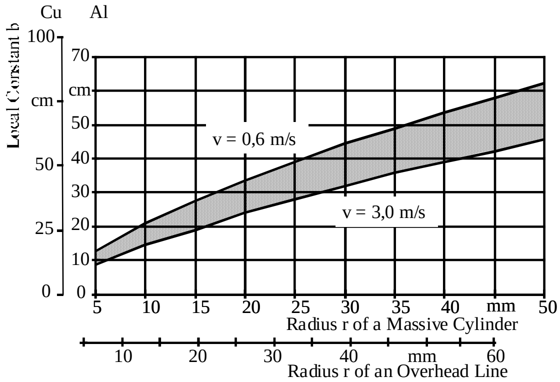

Fig. 5. Local Constant Depending on the Radius

The mapping is done on the total length which covers three times the local constant of the connected conductors and devices.

* The time constant τ has been calculated for conductors and joints. It is a value that indicates the time delay between the load change and the temperature change - (Fig. 6).

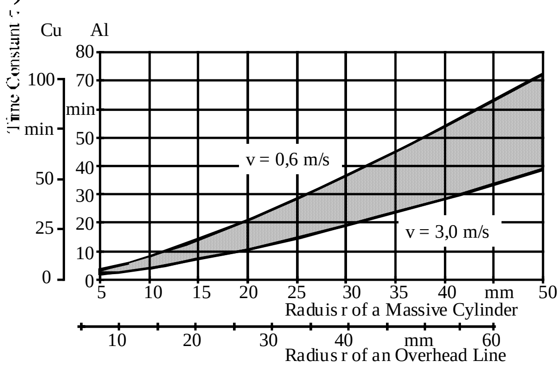

Fig. 6. Time Constant Depending on the Radius

* The error in calculating the performance factor is mainly influenced by those failures which occur when measuring the joint temperature $\Delta\vartheta_J$, the load current $\mathbf{I_l}$, the wind speed **v** and the sun and sky radiation $\mathbf{P_{SS}}$.

* The mean load currents in high voltage power supply systems amount to approx. 30% of the rated current of the installed conductors. The infrared diagnosis requires the load to be min. 35% of the rated current $\mathbf{I_r}$ of the conductors in order to achieve a clear statement on the temperature rise of the joints.

* The timely change of the load current $\mathbf{I_1}$, determines whether or not the joint temperature follows the current load and environmental load quasi-statically or dynamically. The theoretic transition value from the quasi-statical load to the dynamical load is

$$|\mathbf{S_{lim}}| = 0.33\%\ \Delta I_l/I_l\ min^{-1}.$$

The mean load changes occurring in high voltage power supply systems per minute, amount to $|\mathbf{S}| = 0.4\%\ \Delta I_l/I_l\ min^{-1}$, and the daily max values to

$$|\mathbf{S_{max}}| = 3.4\%\ \Delta I_l/I_l\ min^{-1}$$ - (Fig. 7).

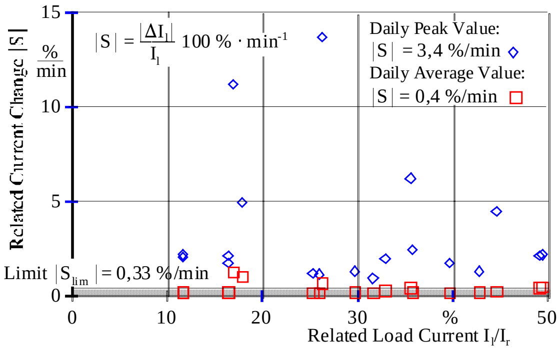

Fig. 7. Related Current Change Distribution

* In the cases $|\mathbf{S}| < 0.33\%\ \Delta I_l/I_i\ min^{-1}$, it will do to determine the performance factor using the joint temperature which is measured once, and applying the efficient load parameters of the static thermal network.

* In the cases $|\mathbf{S}| > 0.33\%\ \Delta I_l/I_i\ min^{-1}$, the performance factor is calculated from the load parameters of the dynamic thermal network for a time period of min. 8 minutes.

* In substations and on overhead lines, the wind speed in the height of the joints is not always measurable. Therefore, a relation that allows to calculate the wind speed **v** on the joints from the measured wind speed in a lower height has been derived from measurements - (Fig. 8).

* At geometrically similar joints with a constant relation between joint surface and conductor of equal length $\mathbf{A_J/A_C}$ = const. and with a statical load and an equal temperature rise, the performance factors are nearly the same. Therefore, the relation between the temperature rise and the performance factor of the joint can be transferred from one electrical joint to another, if they are geometrically similar.

* The example of the bolted T-joints (RIBE 702 107) - (Fig. 9) has been used to develop and test the dynamic thermal networks.

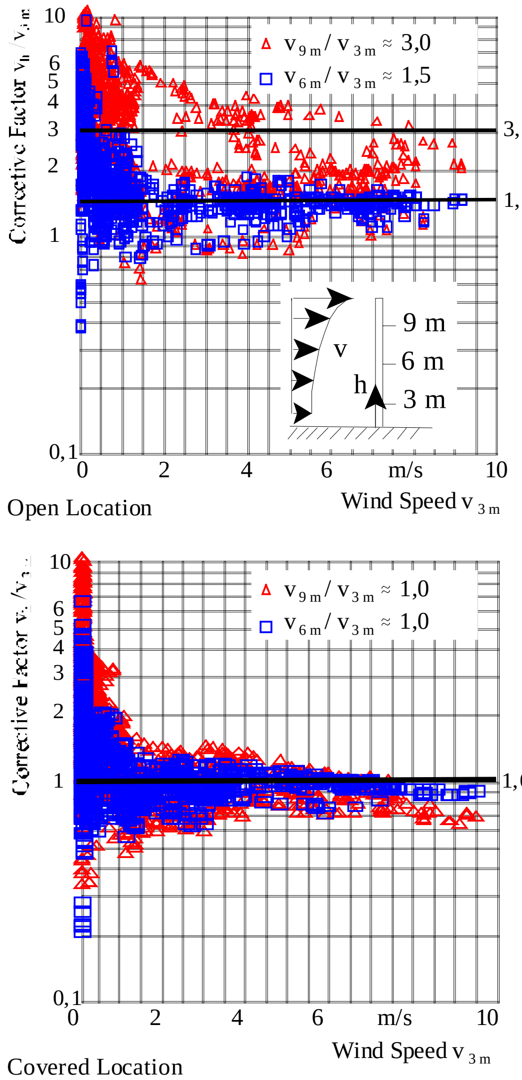

Fig. 8. Wind Speed Depending on the Height

The relation between the temperature rise of the joint and the performance factor has been determined using the static thermal network and the following simplifications - (Fig. 10):

related load current $\mathbf{I_l/I_r}$ = 0.4... 1.0
wind speed **v** = 0.3... 1.6 m/s as well as
sun and sky radiation $\mathbf{P_{SS}}$ = 0... 1000 W/m².

Fig. 9. Bolted T-Joint RIBE 702 107

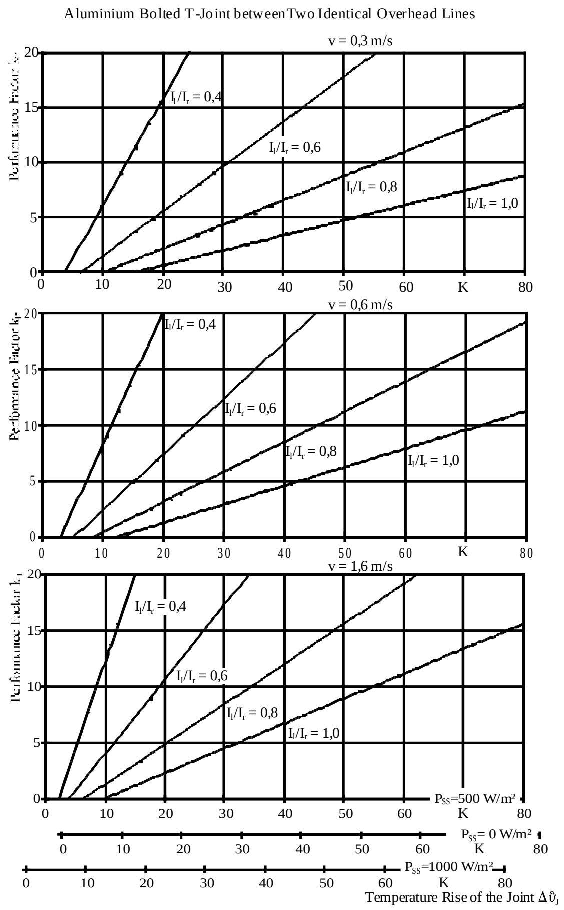

Fig. 10. Determination of the Performance Factor out of the Temperature Rise of the Joint

Determination of the Residual Life Time of the Joints

The chemical ageing model for joints is used to calculate the residual life time, depending on the diagnosed performance factor. This calculation includes the operating time, the material pairing and the joint construction as well as the previous, present and future load current.

* The joints do not carry the current in an even way over the apparent contact surface. Only a small part of this surface - the so-called true contact surface - participates in the transfer of the current. At the constriction areas, the current lines are narrowed and micro-contacts are the result. The additional resistance which results from these restriction areas are called constriction area resistance.

* The contact surfaces are covered by a pollution layer of some Ångström in thickness within a few seconds after brushing or sliding. This pollution layer strongly influences the temperature of the constriction areas. The thickness of the pollution layer between the true contacts is nearly independent of the contact force of the joint and of the radius of the constriction area.

* The ageing of the joints is mainly due to the fact that the constriction area radius a is getting smaller and smaller whereagainst the performance factor $\mathbf{k_U}$ are getting larger and larger. In line with the increased ageing, the continuous quasi-metallic pollution layers grow on the real contact surfaces up to a thickness of $\mathbf{s_F}$ < 100 Å. The resistance of the pollution layer $\mathbf{R_L}$ and the performance factor k_U increase until the joint has reached the temperature limit and fails.

* For Al-Al and Al-Cu joints, the parameters for the ageing equation are known. This equation is used to determine the course of the joint resistance. The ageing equation calculates, for example, the bolted T-joints which are applied in the electrical power engineering. The residual life time $\mathbf{\Delta t_R}$ results from the time until the limit performance factor is reached. The residual life time $\mathbf{\Delta t_R}$ for the contact pairing Al-Al and Al-Cu is calculated in dependence on:

related load current $\mathbf{I_l/I_r}$ = 0.4... 1.0 and
operating time of the joint $\mathbf{t_{OT}}$ = 5... 20 a.

It turned out that the Al-Al joints themselves can be long-term operated with stability even if they are loaded with the rated current of the line conductors - (Fig. 11). Al-Cu joints are only stable for several decades if the load current is smaller than 60% of the rated current of the connected conductors.

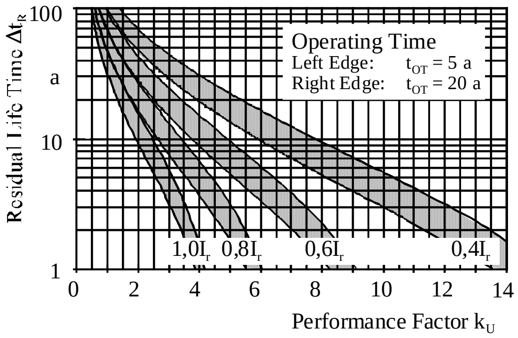

Fig. 11. Residual Life Time of Al/Al-Joints Depending on the Performance Factor

Example of a *RELITE* Evaluation Diagram

The residual life time of the joints is determined by the measured temperature rise according to the described procedure.

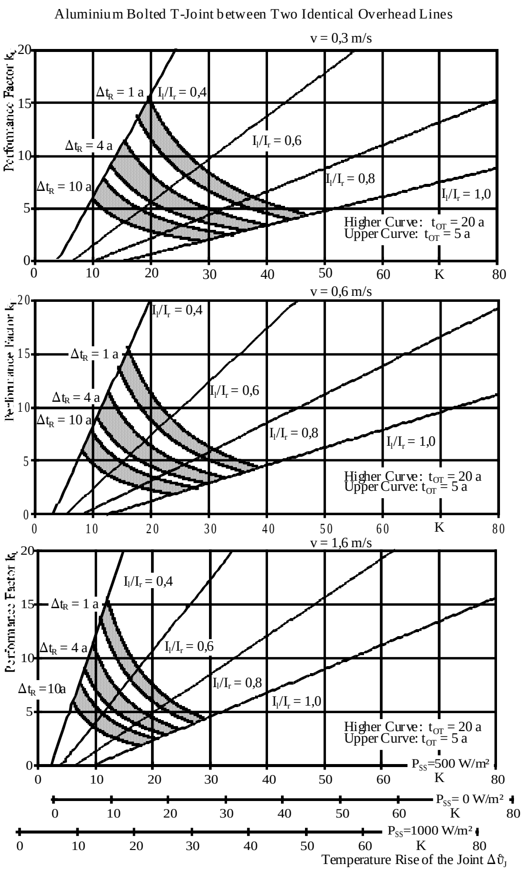

Fig. 12. RELITE Diagnosis on Bolted T-Joints

The performance factor is calculated based on the thermal network model, the residual life time is calculated based on the chemical ageing model.

* Considering the side conditions

related load current $\mathbf{I_r/I_l}$ = 0.4... 1.0

wind speed **v** = 0.3... 1.6 m/s

sun and sky radiation $\mathbf{P_{SS}}$ = 0... 1000 W/m²

operating time of the joint $\mathbf{t_{OT}}$ = 5... 20 a

contact pairing Al-Al

residual life time $\mathbf{\Delta t_R}$ = 1a... 10a

the *RELITE* procedure has been worked out for the bolted T-joint RIBE 702 107 - (Fig. 12).

Fig. 13. Different Types of Infrared Systems in Use

* *RELITE* diagrams are available for the *device connections of disconnectors, circuit breakers and transformers, for the*

contact system of disconnector and all types of connections between busbars and lines for out- and indoor conditions from low to high voltage - (Fig. 13).

Statistical Results

The explanations will be finished with a practical example and its conclusions. Approx. 700 electrical joints and contacts of a 6-kV substation supplying an important part of a chemical plant were to be diagnosed. The three-busbar system with approx. 30 feeders was about 20 years old. It consisted predominantly of 800 mm² and 2400 mm² aluminium busbars.

For every joint, it was necessary to define the residual life time considering the momentary and prospective load current $\mathbf{I}_l$. The ambient conditions wind speed and radiation were assumed to be zero.

The joints and contacts were divided into 4 groups:

- residual life time more than 10 years
- residual life time between 4...10 years
- residual life time between 1...4 years
- residual life time less than 1 year.

The last one represents the classic hotspot, which has to be maintained immediately.

The joints and contacts examined can be divided at least into three categories:

- bolted connections between busbar and cable terminals: mainly Al/Al - (Fig. 14)
- bolted device interface at circuit breakers and disconnectors and current transformers: mainly Al/Cu - (Fig. 15)
- disconnect contacts: Ag coated - (Fig. 16)

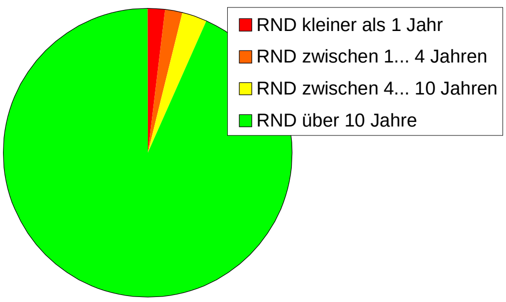

Fig. 14. Synopsis of all Bolted Connections Between Busbars and Cable Terminals

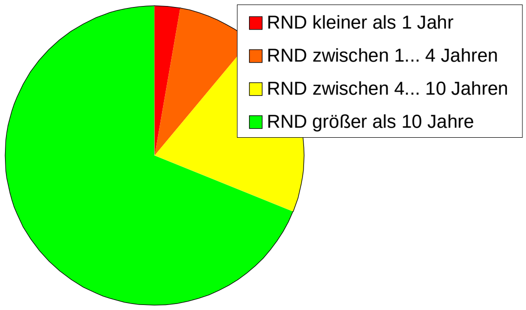

Fig. 15. Synopsis of all Bolted Device Interfaces

The smallest rate of failure occurred in the category of the joints connecting aluminium with aluminium bars (e.g. busbar and cable connections).

About 12 % of the joints in the category of the connections on terminals of circuit breakers and disconnectors have a residual life time less than 4 years. The rate of failure has increased due to the more problematic combination of copper and aluminium.

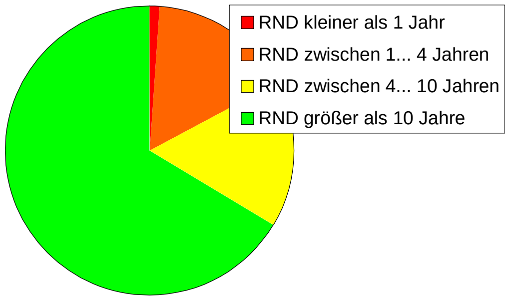

Fig. 16. Synopsis of all Disconnect Contacts

The group of the disconnect contacts is the most critical one with more than 18 % contacts having a residual life time less than 4 years. This fact results from a fundamentally different ageing behaviour caused by contact forces that are relatively small compared to those occurring in bolted joints.

Taking the related load current into consideration, a dependence of the residual life time on the related load current can be stated for all examined joints and contacts - (Fig. 17).

- Firstly, it can be concluded that the probability of hotspots is independent of the current as long as the related current is above 20 % (red bar).

- Secondly, the number of joints and contacts which are partly aged increases with the current (orange and yellow bar).
- Finally, if the system was run at nearly 90 % rated current and all hotspots had been maintained before, the probability to fail within 4 years would be about 12 % and within 10 years about 55%.

These conclusions apply only to the examined substation and can be generalised only with reservation.

With the help of such results, it is easy to decide how long the residual life time of a joint is. The decision for the next maintenance can be scheduled exactly. A long-term and status-oriented maintenance and repair can now be implemented. The reliability of the installations increases whereas the maintenance costs decrease.

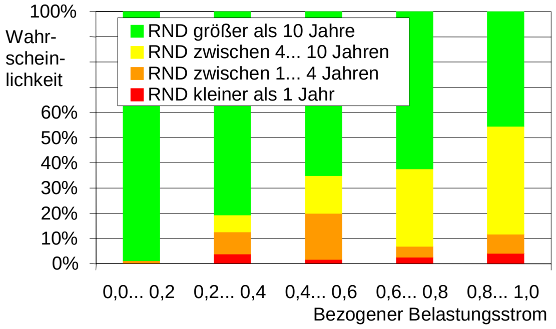

Fig. 17. Probability of the Determined Residual Life Time Depending on the Related Load Current

[1] Böhme, H.:
Mittelspannungstechnik. Berlin: Verl. Technik, 1992

[2] Bergmann, R.:
Zum Langzeitverhalten des Widerstandes elektrischer Verbindungen. Düsseldorf: VDI-Verl., 1996

[3] Rogler, R.-D.:
Infrarotdiagnose an Verbindungen der energetischen Elektrotechnik. Düsseldorf: VDI-Verl., 1999

[4] Rigdon, W. S.:
“Emissivity of Weathered Conductors After Service in Rural and Industrial Environments”.
In: AIEE Transactions P. III Power Apparatus and Systems Vol. 81