A Diagnostic System for Live Electrical Joints in Power Transmission Systems

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Abstract

The resistance of an electrical joint increases depending on load current and environment until the temperature of the joint reaches a critical level, i. e. hot spots occur. To avoid such failures the joints have to be diagnosed and, if necessary, maintained. A widely applied method to inspect electrical joints is to measure the temperature rise and to compare it with empirical limit temperature rises that are assigned to several decisions. Due to unconsidered parameters this method is not sensitive enough to allow a long-term maintenance concept. To overcome this shortcoming, the resistance of the joint has to be determined from the measured temperature. All the processes of producing, transmitting and storing power are modelled by a thermal network in which the resistance is the only unknown quantity. It can be ascertained by comparing measured and calculated temperatures. The resistance is used to determine the residual life time which depends strongly on this momentary resistance of the joint and the further load current of the line. This method will be described in a following paper.

1 Introduction

Under heavy electrical and environmental loads along with poor installation, electrical joints in power transmission systems can become hot spots which lead to a failure of the joint and a loss of power transmission. The state of the joints is, therefore, supervised with the help of various diagnostic methods. One of the frequently used methods is the infrared diagnosis. The temperature of the joint is taken by an infrared camera without any interference with the power system operation.

2 Assessment of the Temperature of the Joint

According to [1], the state of the joint is determined from its temperature rise $\Delta\vartheta_{\text{tak}}$. This quantity equals the temperature difference between the connector ϑ_{con} and the environment ϑ_0. It is assumed that this temperature rise is caused by the load current I_L. Both values are taken simultaneously. In order to evaluate the state of the joint, the established temperature rise $\Delta\vartheta_{\text{tak}}$ is converted to the temperature rise $\Delta\vartheta_{\text{eva}}$ which would have resulted at the maximum load current, i. e. at the rated current I_{rat} of the installation or the device:

$$\Delta\vartheta_{\text{eva}} = \left(I_{\text{rat}}/I_L\right)^2 \Delta\vartheta_{\text{tak}}, \tag{1}$$

If the temperature rise determined in eq. (1) amounts to

$\Delta\vartheta_{\text{eva}} < 10$ K,

the operation of the installation can be continued without restrictions.

For $10 \text{ K} < \Delta\vartheta_{\text{eva}} < 35$ K,

a corrective maintenance will be necessary during the next planned maintenance.

For $35 \text{ K} < \Delta\vartheta_{\text{eva}} < 70$ K,

a corrective maintenance will be required within a month (at $I_L > 0.6\, I_{\text{rat}}$) or a year (at $I_L < 0.6\, I_{\text{rat}}$).

For $\Delta\vartheta_{\text{eva}} > 70$ K,

an immediate corrective maintenance of the joint will be necessary.

If the state of a joint is to be determined from its temperature rise, the following additional conditions must be considered:

- the measuring must not be influenced by rain, mist or fog,
- the load current should be $I_L > 0.5\, I_{\text{rat}}$,
- the temperature of the joint should be steady-state,
- the wind speed has to be $v < 6$ m/s.

It is shown in [1] that those additional conditions of the load current and the environment must be met in order to detect poor joints and to determine the state of repair of a joint reliably.

These additional conditions can be explained as follows:

- Due to the evaporation of moisture on surfaces the temperature of the device is affected so strongly that an assessment of the joint becomes impossible. Mist and fog have an unpredictable hindrance on the radiation which is emitted by the device surface and absorbed by the sensor of the infrared camera. Therefore, the taking of the temperature of the joint ϑ_{con} via its thermal radiation is impossible while mist or foggy conditions prevail.

- In order to attain temperature differences which can be taken with the necessary precision, the load current I_L has to be high.
- Steady-state temperatures at the joints are required because only static values can be judged relatively simply. This also means that the load current, the wind, the ambient temperature as well as the solar and sky radiation must not change before the measuring during a period of at least three times the thermal time constant τ of the joint. The influence of the time-dependent load current on the result of the diagnosis is described in clause point *Load Current*.
- It is known [2] that wind speeds above $v = 0.6$ m/s influence the temperature of a joint considerably. The question of the influence of the wind on the result of the diagnosis is dealt with in clause *Wind Speed*.

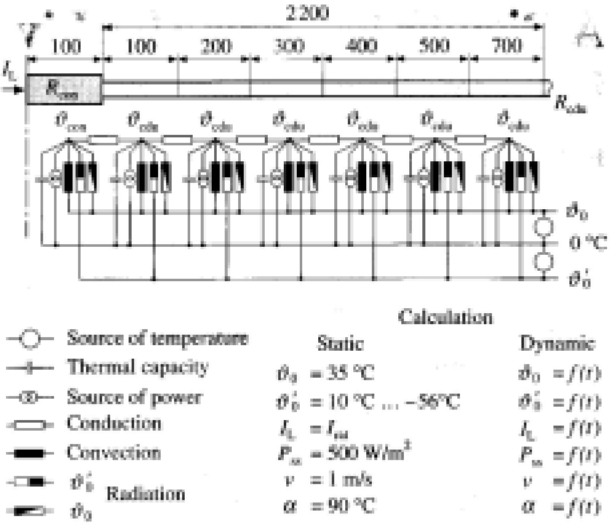

Fig. 2. Thermal network of a connector (numerical values in mm)

3 Shortcomings

The effects of the current method resulting from weak and unconsidered influencing parameters shall be demonstrated in the following.

3.1 Temperature of the Higher Atmospheric Layers

Depending on the amount of cloud, a certain part of the emitted power is radiated to the higher layers of the atmosphere. A quarter up to a third of the emitter surface is affected by this process.

The temperature in this region might reach temperatures down to $\vartheta'_0 = -56$ °C [2] locally. It can increase up to 10 °C (**Fig. 1**) when the sky is completely clouded over.

The influence of the higher atmospheric layers cannot be neglected any longer, especially on less windy summer days.

3.2 Load Current

The influence of a change of the load current on the diagnostic result will be demonstrated for a connector with two ACSR conductors 550/70 mm^2. The conductor temperature ϑ_{cdu} and the temperature of the connector ϑ_{con} are calculated with the help of a thermal network [3] (**Fig. 2**).

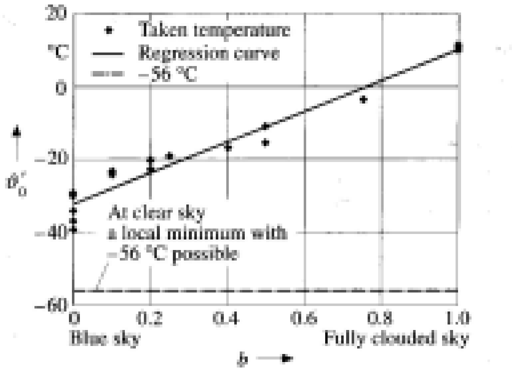

Fig. 1. Temperature of the higher atmosphere ϑ'_0 (b amount of cloud)

The following effects are all taken into account: The heat transfer processes (radiation and convection into the environment, radiation into the higher atmospheric layers, heat conduction), the heat storage and the heat sources (power of the solar and sky radiation P_{ss} and power loss P_{I^2} caused by the load current I_L in the connector R_{con} and in the conductor R_{cdu}):

$$P_{I^2} = I_L^2 \, R_{con;\,cdu}, \tag{2}$$

The temperature of the connector ϑ_{con} depends strongly on the performance factor k:

$$k = \frac{R_{con}}{R_{cdu}} = R_{con} \, \frac{A_{cdu}}{\rho(\vartheta)\, l_{con}}, \tag{3}$$

where l_{con} is the length of the connector.

A connector with a performance factor of $k = 1$ at rated current, which secures a lifetime of at least 30 a [4], is, according to [1], evaluated as follows (**Fig. 3**):

- In the case of a static load with the current $I_L = 0.5\, I_{rat}$, the temperature rise of the connector amounts to $\Delta\vartheta_{tak} = 8.5$ K. According to eq. (1), the temperature rise to be evaluated is $\Delta\vartheta_{eva} = 34$ K. Taking into account the criteria established before, the joint has to be repaired when the next planned maintenance is carried out.
- If the current is increased from $I_L = 0.5\, I_{rat}$ to $I_L = I_{rat}$ within 1 h, the apparent temperature rise determined in accordance with eq. (1) will decrease due to the thermal inertia. The joint has to be repaired during the next maintenance.
- If the diagnosis is carried out while the current is reduced from $I_L = I_{rat}$ back to $I_L = 0.5\, I_{rat}$, the apparent temperature rise according to eq. (1), will require that

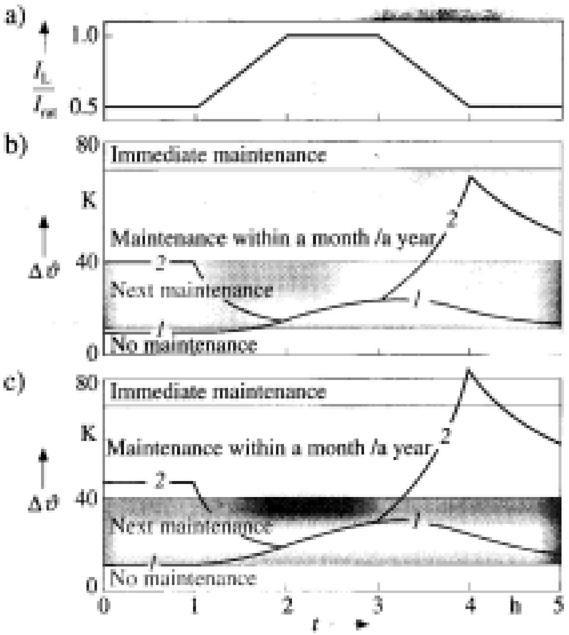

Fig. 3. Influence of a changing load current on the temperature rise of a bolted connector ($S_{con}/S_{cdu} = 4.0$; S_{con} surface connection; S_{cdu} surface conductor)
a) $I_L/I_{rat} = f(t)$
b) Temperature rise $\Delta\vartheta = f(t)$, $k = 1.0$ (1: $\Delta\vartheta_{tak}$; 2: $\Delta\vartheta_{eva}$)
c) Temperature rise $\Delta\vartheta = f(t)$, $k = 2.0$ (1: $\Delta\vartheta_{tak}$; 2: $\Delta\vartheta_{eva}$)

the joint at a load of $I_L > 0.6\ I_{rat}$ has to be replaced within a month.

- If the performance factor of the joint is $k = 2$ and the temperatures are taken at $t \approx 4$ h (Fig. 3), it will be concluded that the joint has to be replaced immediately. However, a joint with a performance factor of $k = 2$ after several years of operation can be loaded with rated current for many more years without becoming a hot spot.

3.3 Wind Speed

The influence of wind speeds in the range from 0.6 m/s to 6 m/s on the result of the diagnosis, according to [1], is demonstrated with two examples, namely with a compression connector and a bolted connector. The temperature rise as a function of the wind speed for the two joints in outdoor atmosphere at a current load of $I_L = I_{rat}$ is calculated for various performance factors k using a thermal network (Fig. 2). The steady-state temperature of a reference conductor without joints amounts to $\vartheta_{cdu} = 80$ °C at said current load, wind speed of $v = 0.6$ m/s and ambient temperature of $\vartheta_0 = 35$ °C and $\vartheta'_0 = -56$ °C, respectively [2] (radiation into higher atmospheric layers).

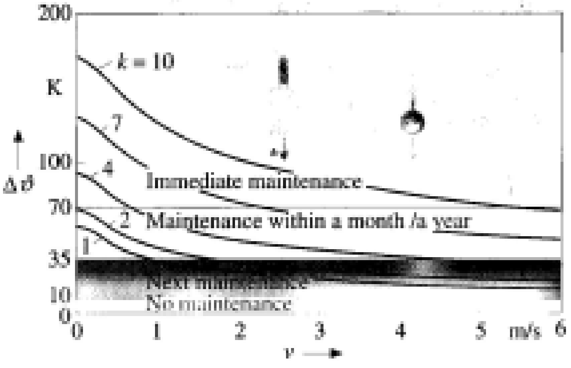

Fig. 4. Influence of the wind speed v on the temperature rise $\Delta\vartheta$ of a compression connector ($S_{con}/S_{cdu} = 1.6$; parameter: performance factor k)

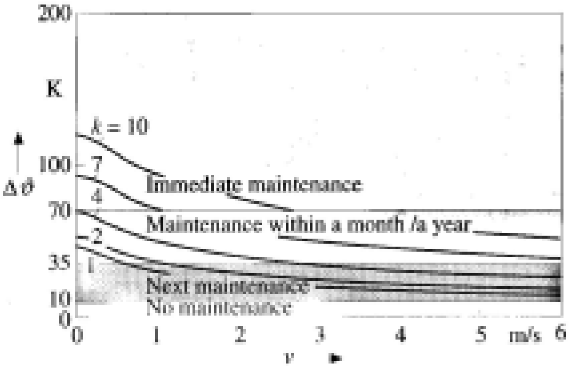

Fig. 5. Influence of the wind speed v on the temperature rise $\Delta\vartheta$ of a bolted connector ($S_{con}/S_{cdu} = 4.0$; parameter: performance factor k)

The simulation reveals that the compression connector has to be replaced at any rate (**Fig. 4**) because the surface for thermal transmission is relatively small compared to the conductor surface ($S_{con}/S_{cdu} = 1.6$).

Even the joint with a performance factor of $k = 1$ will be diagnosed to be a weak point. Long-term tests have revealed that such a performance factor normally secures a stable operation for at least 30 a [4]. Using the current diagnosis method it would be concluded that this joint must be replaced during the next planned maintenance if the measurements are taken at wind speeds above 1 m/s or within a month at wind speeds below 1 m/s. The influence of the wind speed on the evaluation of the state of the joint becomes obvious. Poor joints with performance factors of $k > 7$ are reliably recognized as weak points by this valuation.

Different conclusions will be reached if poor joints with relatively large surfaces for thermal transmission ($S_{con}/S_{cdu} = 4.0$), such as bolted connectors, are evaluated. Even a joint with a performance factor of $k = 10$ will not be recognized as extremely critical if measurements are taken at wind speeds above 2.7 m/s (**Fig. 5**).

Long-term tests of this type of connector have shown that the joint resistance begins to intermit even at performance factors of $k = 3.5$ (**Fig. 6**) and above. The melting temperature will then be reached at the bottleneck points of this joint.

The analysis clearly demonstrates that for this type of connector once again joints with uncritical performance factors $1 < k < 2$ will be evaluated as being weak points with measurements taken at wind speeds below 1 m/s.

The analysis shows clearly that, on the one hand, weak points are not recognized reliably and that, on the

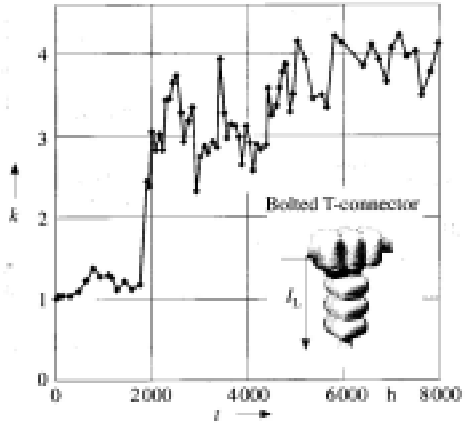

Fig. 6. Intermitting performance factor k of a bolted T-connector

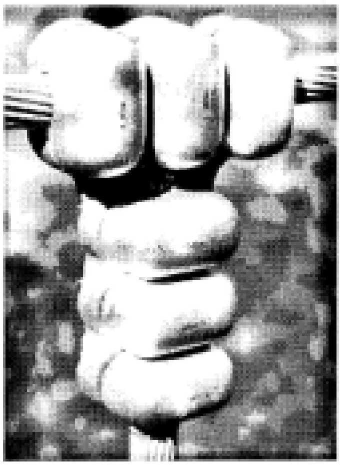

Fig. 7. Investigated bolted T-connector

other hand, good joints can be declared weak points erroneously.

4 Determination of the Joint Resistance R_{con}

The previous considerations have revealed that the temperature rise $\Delta\vartheta_{\mathrm{exc}}$ alone is not a reliable criterion to judge joints in need of repair.

The joint resistance R_{con} is reflected in the temperature characteristic and the temperature distribution of the connector and the connected conductor depending on the actual load current and the environmental parameters. Therefore, it becomes possible to develop a dynamic thermal network (Fig. 2) including all quantities determining the temperature characteristics. Referring to the heat sources, these are the load current $I_L(t)$ and the solar and sky radiation $P_{\mathrm{ss}}(t)$.

As far as the thermal resistances are concerned, the convective resistances are strongly affected by the wind. Apart from the wind speed $v(t)$ the wind direction $\alpha(t)$ must be included in the calculation of these resistances. The ambient temperature $\vartheta_0(t)$ near the ground will also be taken into account. The temperature of the higher atmospheric layers is estimated as a function of the amount of cloud to $\vartheta_0' = -56\ ^\circ\mathrm{C} \rightarrow +10\ ^\circ\mathrm{C}$.

The following ranges for the change of the load current I_L and the ambient temperature ϑ_0 have been gained from experience:

$$\vartheta_0 = -5\ ^\circ\mathrm{C} \ldots 35\ ^\circ\mathrm{C}, \quad \dot{\vartheta}_{0,\max} = \frac{3\ \mathrm{K}}{1\ \mathrm{h}};$$
$$I_L = 0.1\, I_{\mathrm{rat}} \ldots 1.0\, I_{\mathrm{rat}}, \quad \dot{I}_{L,\max} = \frac{0.5\, I_{\mathrm{rat}}}{1\ \mathrm{h}}. \tag{4}$$

All the other parameters influencing the temperature of both the joint and the connected conductor, such as the emissivity ε and the absorption α' of the surfaces, the geometry of the arrangement and the specific electrical resistance of the conductor material, are assumed to be constant.

Using the example of a bolted T-connector (**Fig. 7**) it will be demonstrated how and to which degree of exactness, the joint resistance R_{con} can be determined with the dynamic thermal network (Fig. 2).

At intervals of $\Delta t \geq 1$ s the load parameters which fluctuate in time are recorded, stored and transferred into a computer and here, into the thermal network for further processing. The whole analysis is carried out by a measuring and evaluation system (**Fig. 8**). The joint resistance R_{con} is determined with the *RLC*-network programme "Pspice 5.4" that was originally created for electrical purposes.

By comparing this resistance R_{con} to limited values, it can be estimated if and when a replacement of the connector is necessary. More exact information will be obtained if the residual service life is determined starting out from the resistance R_{con} and the load to be expected with the help of a mathematical ageing model [4].

Over a time less than 8 min the parameters which are necessary for the calculation of the resistance R_{con} were measured (**Fig. 9**). It is obvious that particularly the load current I_L and the wind speed v strongly fluctuate within this period and lead, in turn, to fluctuations of the joint temperature ϑ_{con}.

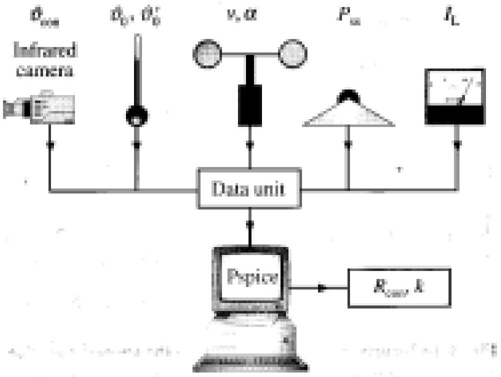

Fig. 8. Measuring and evaluation system

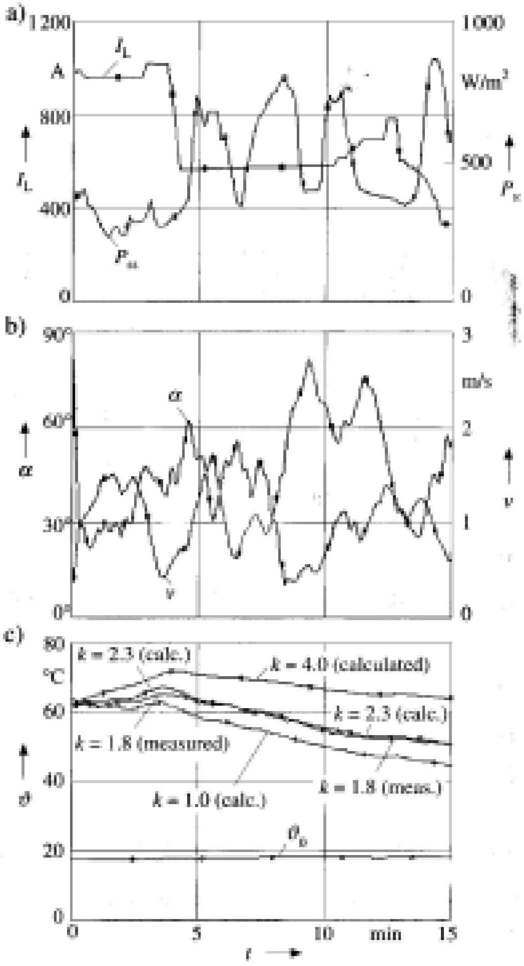

Fig. 9. Example of the determination of a performance factor
a) $I_L = f(t)$ and $P_{ss} = f(t)$
b) $\alpha = f(t)$ and $v = f(t)$
c) $\vartheta = f(t)$

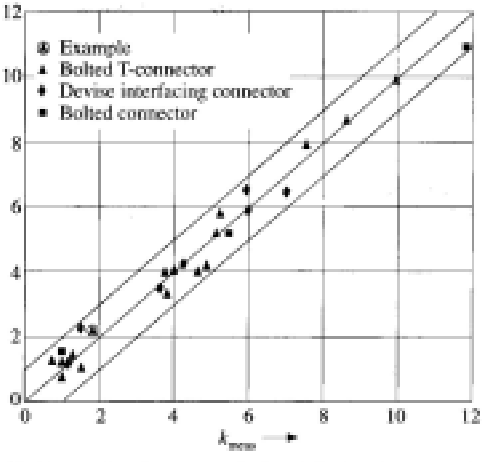

Fig 10. Comparison between calculated (k_{det}) and measured (k_{meas}) performance factors

The temperature characteristics of the joint were calculated too low and too high assuming performance factors $k = 1.0$ and $k = 4.0$, respectively. The performance factor at which the taken temperature characteristic corresponds best to the calculated one amounts to $k = 2.3$. The integral averages of both temperature rise characteristics were chosen as a criterion for the alignment. The performance factor of the connector measured by the current-voltage-method was $k = 1.8$.

The evaluation of the errors in this method has revealed that performance factors can be determined with a precision of $\Delta k \leq 1.0$. This error range was confirmed by comparing the calculations with the measurements (**Fig. 10**).

The period of time over which the temperature characteristics must be taken and calculated corresponds to the triple thermal time constant τ of the joint plus the time during which the alignment of the taken and calculated temperature characteristics is achieved. If the calculation is started with the true initial temperatures gained from a thermal snapshot with the infrared camera, the measuring time can be reduced to the time of alignment. The tests of bolted T-connectors have shown that the time of resistance determination is only 8 min.

5 Conclusions

It has been demonstrated that the conventional diagnosis method which is used to assess the state of joints in service can lead to wrong results since, on the one hand, fully functional joints are evaluated as needing replacement and, on the other hand, dangerously aged joints are not discovered. Using the method introduced in this paper the joint resistance R_{con} is determined from the temperature of the joint ϑ_{con}. In this way, much more reliable conclusions can be drawn on the actual state of the joint under consideration. The residual service life can be determined out of the previous and the prospective load currents.

The method was employed in several transformer substations with reliable success.

6 List of Symbols and Abbreviations

ϑ_{cdu}	temperature of the conductor
ϑ_{con}	temperature of the connector
ϑ_{tak}	taken temperature rise
ϑ_{eva}	evaluated temperature rise
I_L	load current
I_{rat}	rated current
ϑ_0	ambient temperature
ϑ_0'	temperature of the higher atmosphere
v	wind speed
α	wind angle
P_{ss}	solar and sky radiation
S_{cdu}	surface of the conductor
S_{con}	surface of the connector
A_{cdu}	cross-section area of the conductor
l_{con}	length of the connector
ρ	resistance
k	performance factor

t	time
$(\dot{\ })$	derivation
Δ	difference, rise
b	amount of cloud
ACSR	Aluminium cable steel-reinforced

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