AGEING OF HIGH CURRENT JOINTS IN POWER TRANSMISSION AND DISTRIBUTION SYSTEMS

Falk BLUMENROTH*, Helmut LÖBL*, Steffen GROßMANN*, Ralf PUFFER, Detlef HUSSELS****
***Technical University of Dresden - Germany**
blumenroth@ieeh.et.tu-dresden.de, loebl@ieeh.et.tu-dresden.de, grossmann@ieeh.et.tu-dresden.de
****E.ON Netz GmbH, System Technology Transmission Lines - Germany**
Detlef.Hussels@eon-energie.com, Ralf.Puffer@eon-energie.com

ABSTRACT

The liberalization of the power market and the increasing number of regenerative energy producers (esp. wind parks) cause an increasing current load on existing overhead transmission lines. All components of the electrical circuit have to be able to carry the increased current load. High current joints are an important part of electrical circuits. The effect of higher currents on the ageing process of joints has to be investigated in order to avoid failures.
As a result of the ageing process the joint resistance increases and therewith the electrical losses in the joint. A higher temperature of the joint caused by the increase of losses can lead to a failure of the joint. The ageing of joints depends on the quality of the installation, the ambient conditions and the current load.
In long term tests lasting up to three decades the ageing processes on different types of static high current joints have been investigated. It is possible to diagnose and to estimate the residual life time of a joint.
A calculation model of the long time behavior of electrical joints under high current load is given.

Key words: long time behavior, ageing, high current joints, diagnostics, residual life time

INTRODUCTION

Elements and devices of the power transmission and distributions systems are connected by a large number of different electrical joints which are subject to ageing processes. The electrical resistance of joints R_j will increase during this ageing time. Because of this, the joint temperature caused by increased power losses can be so high that the joints themselves or the associated insulation material will be destroyed. Thus the reliability of the electrical power supply system will be determined significantly by the high current joints [1].
Due to the liberalization of the power market and the increasing number of regenerative energy producers the current load I and therewith the power losses P_j in the joints in the electric supply systems increases.

$$\Delta J_j \sim P_j = I^2 R_j \qquad (1)$$

The increased joint temperatures $\Delta\vartheta_j$ accelerate the ageing of the electrical joints. Despite accelerated ageing, the electrical joints should work reliably and maintenance free during the expected lifetime of about 60 years of the electrical devices.
In order to design a reliable joint or assess a joint which has already been in service for many years, it is necessary to know its ageing behavior. The most significant quantity to assess the ageing of high current joints is the joint resistance R_j.
In the following is presented:

- fundamentals of the electrical joints
- the possible ageing mechanisms of electrical joints
- a calculation model of the long time behavior of electrical joints
- diagnostics and estimation of the residual life time of a joint

The paper gives an overview on the ageing of high current joints and demonstrates the influence of the current load and the quality of the installation on the ageing behavior of the electrical joint.

FUNDAMENTALS

If two conductors are connected to each other by their surfaces, the current does not flow with an uniform distribution over the apparent contact area A_a (Fig 1). Depending on the surface roughness, the contact hardness and the oxide or other electrically insulating layers, the true contact area A_t is only a fraction of the apparent contact area A_a that participates in the current transfer. Generally, the interface becomes electrically conductive only when metal-to-metal contact spots ("a-spots") are produced, i.e. where electrically insulating films are ruptured or displaced at contacting surface asperities [2].

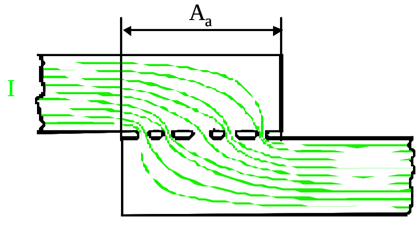

Fig 1 current field in an electrical busbar joint with contact spots

To compare electrical joints of different types and dimensions, a performance factor k is introduced. It is the relation between the joint resistance R_j and the reference resistance R_r given by the resistance of the conductor of the same length l as the joint (Fig 2).

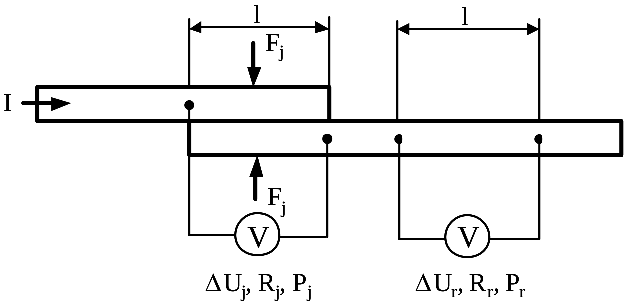

Fig 2 performance factor k of electrical joints

$$k = \frac{R_j}{R_r} = \frac{\Delta U_j}{\Delta U_r} = \frac{P_j}{P_r} \qquad (2)$$

The ideal performance factor k_I = 0,5 for the example in Fig 2 is the performance factor of a joint where the apparent contact surface A_a is current carrying.

Experiments have shown that a start-off performance factor of busbar joints for the German standard [3, 4] is between k_0 = 0,63 and 1,33 for a long service time of low and stable joint resistance [1]. To fulfill these requirements, the conducting areas (true contact area or number of “a-spots”) between the conductors have to be large. This can only be achieved by clean surfaces and high contact forces, when the microscopic surface roughness is plastically deformed and the insulating layers are destroyed [2], [5], [6]. The joint resistance depends on the contact force. A high contact force generates a low joint resistance and therewith a low performance factor k [6].

AGEING OF ELECTRICAL JOINTS

The ageing of electrical joints is determined by different ageing mechanisms: chemical, interdiffusion creep/stress relaxation, gross plastic fretting and electromigration. All ageing mechanisms can take place simultaneously and depend on the contact temperature.

A joint is considered as broken down when the temperature of the contact spots reaches the melting temperature of the conductor material. If this is the case, the performance factor is called the limiting performance factor k_l. The limiting performance factor is not a constant value. It depends on the design and the load of the joint [1].

Chemical ageing describes the corrosion processes in the interface between both conductors, especially by base metals like aluminum and copper. The chemical reaction between the conducting material and the environment results in a growing insulating layer at the constriction area in the joint. Consequently the electrical field becomes inhomogeneous and the joint resistance increases. Generally the ageing behavior of a joint caused by chemical changes at the constriction areas can be divided into three phases (Fig 3). During the first phase (formation) chemical reactions go on unhindered and the resistance is increasing. The products of reaction (insulating layers) deposit on the surface of the constriction area. They have the same effect like a protective layer. Consequently further chemical processes go slower, because one partner of reaction has to migrate through the protective layer. In the second phase of ageing (relative stability) the joint resistance increases only very slowly, because of the protective layer. Nevertheless the power loss in the joint is increasing as a result and the joint temperature too (Equ. 1).

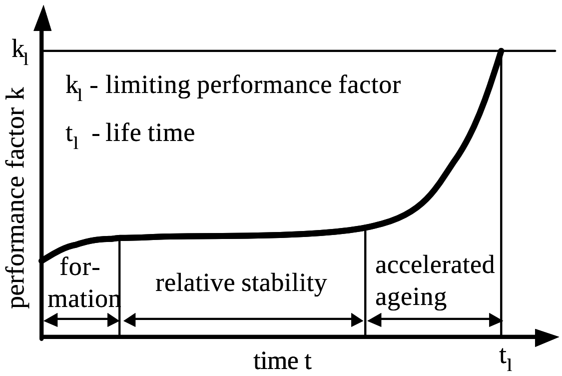

Fig 3 ageing behavior of an electrical joint in principle

In the third phase (accelerated ageing) the rate of chemical processes increases due to the higher joint temperature. During the accelerated ageing the joint resistance increases considerably. The temperature can be so high that the melting temperature is reached on the constriction areas. Due to this melting the constriction area can be larger and so the joint resistance can decrease. This effect of intermitting resistance is depending on the load and the design of the connection. Therefore, the life time of the joint is considered as out of order if the melting temperature is reached (k_l).

Interdiffusion ageing describes the process when atoms from one metal diffuse into the other one and intermetallic phases with higher resistance as the pure metal are resulted in the constriction area, if conductors with different metals are connected (for instance Al and Cu) [7].

Creep/stress relaxation ageing depending on mechanical stress and temperature cause a continuous lowering of the joint force. The joint resistance depends on the joint force. A high joint force generates a low joint resistance. If the so-called minimum force of a joint is not kept the joint resistance increases rapidly. Creep/stress relaxations means thereby, that the initial elastically deformation of the conductor material will depend on the time transformed in plastically deformation. The processes which cause the reduction of force are the motion of vacancies, grain boundaries and dislocation in the material, which are also known as recovery.

Gross plastic fretting ageing is wear and surface damage in the interface between two conductors, especially by plug-in power connectors, and cause a higher joint resistances [9]. In power applications, the silver coated copper contacts are subjected to high contact forces (typically 10 – 100 N) and thus inevitable deform plastically already when mated under stationary conditions. Fretting is thereby the relative motion between two contact members. In electrical joints the amplitude of displacements can vary in a very wide range. Electrically (AC) induced vibrations normally cause amplitudes in the µm-range, thermal expansions cause amplitudes in the mm-range while the breaking movement of the joint may be in the cm-range.

Electromigration ageing describes the diffusion of atoms from the area of high current density, also the constriction area, into areas of low current density. As a result from the diffusion a lot of vacancies stay in the constriction area and cause a higher resistance.

CALCULATION OF THE LONG TIME BEHAVIOR OF ELECTRICAL T - JOINTS

In standards like DIN, VDE and IEC different tests to determine long-term acceptability for joints lasting a few weeks only (for example 1 000 ON-OFF-load cycles with test current) are described. Nevertheless, with these tests it is not possible to estimate the long time behavior of the tested joints [1].

Therefore investigations on the long time behavior in long-term tests, starting 30 years ago up to now, have been carried out on different types of static high current joints. The long-term tests point out that chemical and interdiffusion (Al-Cu joints) are the most important ageing mechanisms for high current joints in outdoor air.

Long-term tests on over 400 busbar joints with different materials (Al-Al, Al-Cu), current-loadings and environmental conditions (transformer oil, indoor and outdoor air) have been carried out. Based on the results of these tests and theoretical investigations a mathematical model which describes the chemical/interdiffusion ageing process depending on the conductor material, the connection design, the assembly quality and the loading has been developed [1].

$$\dot{k} = (k - k_l)\,\frac{d\, e^{-\left(\frac{b}{R\,T_C} + \frac{1}{2}\right)}}{\left(\frac{t}{t_0}\right)^m t_0} \qquad (3)$$

The parameters for Aluminium-to-Aluminium joints m = 0,487, b = 9709 J/mol and d = 0,1 are determined from long term tests for a variety of joints. The average lifetime of a joint in electric power systems is not interesting from a reliability standpoint, but the lifetime of the joint which fails first is very important.

Therefore the parameters m, b and d of the joint with the fastest ageing behavior (worst case) have to be determined. With help of the ageing model the influence of several parameters (current I, start-off performance factor k_0, ambient temperature ϑ_0) on the lifetime can be estimated [1]. An example is an Al-T-joint paired with a Al/St wire. If the current I (k_0 = 1) is reduced from 100 % I_r to 70 % I_r, the lifetime increases from 16 to 28 years (Fig 4).

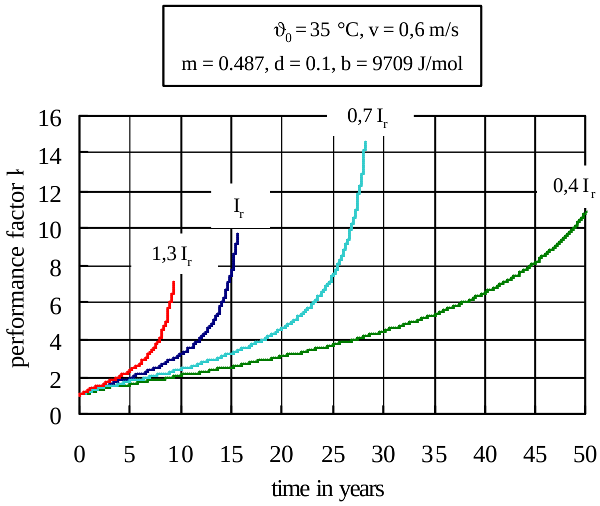

Fig 4 Ageing behavior of an Al-T-joint paired with an Al/St wire depending on the current I

If the quality of installation of the joint is good a decrease of the start-off performance factor from k_0 = 1 to k_0 = 0,7 is achieved and the life time increases from 16 to 32 years (Fig 5).

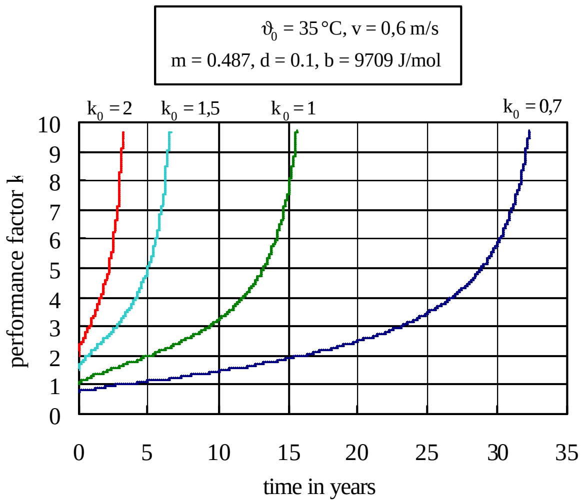

Fig 5 Ageing behavior of an Al-T-joint paired with a Al/St wire by rated current I_r depending on the start-off performance factor k_0

In the laboratory the start-off performance factors of well assembled T-joints were determined in the range from k_0 = 0,6 to k_0 = 0,9.

DIAGNOSTICS AND ESTIMATION OF THE RESIDUAL LIFE TIME

To diagnose and estimate the residual life time of an electrical joint it is necessary to know the momentary resistance of the joint R_j. 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 (Equ. 3). One of the frequently used methods to diagnose electrical joints is the infrared diagnose (Fig 6). The temperature of the joint ϑ_j, which is necessary to determine the resistance, is taken by an infrared camera without any interference with the power system operation (Fig 7). All the parameters influencing the joint's temperature (current I, solar and sky radiation P_{SS}), transmitting (ambient temperature ϑ_0, temperature of the higher atmosphere ϑ_0', wind speed v and wind angle α) and the thermal capacity (material and geometry) are modeled by a thermal network in which the resistance is the only unknown variable. It can be ascertained by comparing measured and calculated temperatures [10].

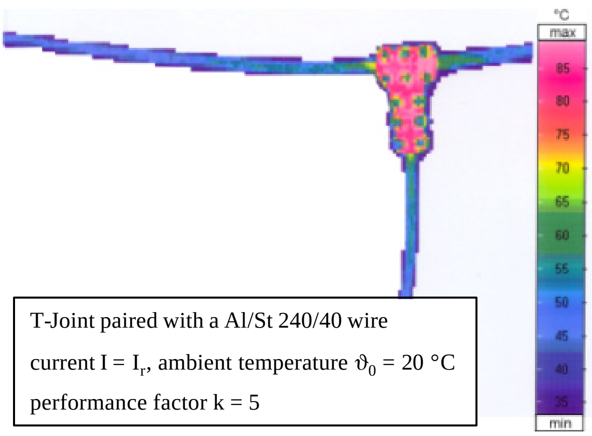

Fig 6 Infrared diagnose of a T-joint

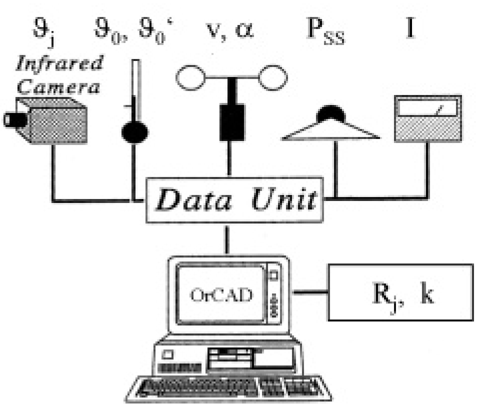

Fig 7 Measuring and evaluation system for diagnose of electrical joints

CONCLUSION

It has been demonstrated that high current joints are subject to different ageing processes, whereas the chemical ageing is the dominating ageing processes. The ageing of joints causes a higher joint resistance and a higher temperature in the joint. That can cause a failure of the joint and therewith an outage of the complete power system within the planned lifetime. Therefore the ageing behavior of electrical joints has been investigated in long-term tests. Based on the results of these tests and theoretical investigations a model which describes the ageing processes depending on the conductor material, the connection design, the assembly quality and the current loading has been developed. The strong influence of the current load and assembly quality on a T-Joint paired with a Al/St wire has been shown.

References

[1] Bergmann, R., Löbl, H., Böhme, H., Großmann, S.: Model to Assess the Reliability of electrical Joints, IEEE, 1996

[2] Slade, P.G. (Editor): Electrical Contacts, New York, Basel, Marcel Dekker Inc., 1999

[3] DIN 43 670 / 12.75, Stromschienen aus Aluminium, Bemessung für Dauerstrom, Beuth Verlag GmbH, Berlin/Köln 1975

[4] DIN 43 670 / 12.75, Stromschienen aus Aluminium, Bemessung für Dauerstrom, Beuth Verlag GmbH, Berlin/Köln 1975

[5] Kassman Rudolphi, A., Jacobson, S. : The role of gross plastic fretting in serviceability and deterioration of power contacts, 18th Int. Conference on Electrical Contacts, 1996, Chicago, pp. 352-362

[6] Schoft, S., Kindersberger, J., Löbl, H.: Reduction of Joint Force by Creep in High Current Joints, 21th Int. Conference on Electrical Contacts 2002, Zürich, pp. 406-412

[7] Wever, H.: Elektro- und Thermotransport in Metallen, Leipzig, 1973

[8] Li, G., Thomas, B. G., Stubbins J.F.: Modeling creep and fatigue of copper alloys, Metallurgical and Materials Transactions A, Vol.31A, No. 10, pp.2491-2502, 2000

[9] Kassman Rudolphi, A.: Tribology of Electrical Contacts, Deterioration of Silver Coated Copper, Dissertation, ACTA Universitatis Upsaliensis, Uppsala 1996

[10] Rogler, R.-D., Löbl, H., Schmidt, J.: A Diagnostic System for Live Electrical Joints in Power Transmission Systems, ETEP Vol. 7, No. 5, pp. 331-336, 1997