Calculation of the Lifetime of Electrical Busbar Joints

R. Bergmann, H. Löbl, H. Böhme, S. Großmann

Abstract

Electrical joints can be a weak points and with it endanger the reliability of electrical power-transmission systems. On the example of Aluminium-to-Aluminium and Aluminium-to-Copper busbar joints is shown how one can get information about the principle ageing behaviour from long-term test. Furthermore a possibility is presented to determine limiting values for the joint resistance and to calculate the lifetime of a joint depending on the construction, conductor material and loading.

1 Introduction

Electrical joint can be subjected to an ageing process which causes an increase of the joint resistance. The resistance can be so high that the joint or the insulating material round the joint will be destroyed. To guarantee a reliable work of the electrical device it is important to know the lifetime of the joint.

The most significant value to assess the condition of a joint is the joint resistance R_j. For the valuation of the joint resistance the performance factor k is used, which is the relation between the joint resistance R_j and the reference resistance R_{ref}:

$$k = R_j / R_{ref}. \qquad (1)$$

The ageing process is caused by creeping of the conductor material and chemical reactions on the constriction areas. Both ageing processes go off parallel but with a different intensity. The ageing of busbar joints will be dominated by chemical processes [1, 2].

In [1, 2] a mathematical model was presented with which the performance-factor characteristic can be calculated with the help of the ageing velocity:

$$\dot{k} = (k - k_{id}) \frac{d\, \mathrm{e}^{-\left(\frac{b}{RT_a} + \frac{1}{2}\right)}}{t^m}. \qquad (2)$$

The ageing velocity depends on the performance factor k, the ideal performance factor k_{id} and the temperature on the constriction area T_a (R: gas constant; t: time; m, b, d: parameters; T_a: temperature on the constriction area). The ideal performance factor k_{id} is a characteristic value of a joint. K_{id} is the smallest performance factor of the joint which is possible.

The parameter m, b and d of the ageing eq. (1) have to be determined from long-term tests. If these parameters are known, it is possible to calculate the lifetime of a joint depending on the construction and loading.

To guarantee the reliable work of the joint resistance is not allowed to go beyond limiting values. At present there exist no limiting values for electrical joint.

Long-term test on over 400 busbar joints with different materials (Al-Al, Al-Cu), current-loading, environments (transformer oil, indoor and outdoor air) have been tested for more than 16 years. Based on the results of these tests and theoretical investigations a mathematical model which describes the ageing process depending on the conductor material, the joint design, the assembly quality and the loading has been developed. It is shown

- which are the most significant factors for the lifetime of a joint,
- how the lifetime and the remaining lifetime of a joint, respectively, can be estimated,
- how limiting values for the joint resistance can be determined, and
- which tests are suitable to get information about the ageing behaviour of joints.

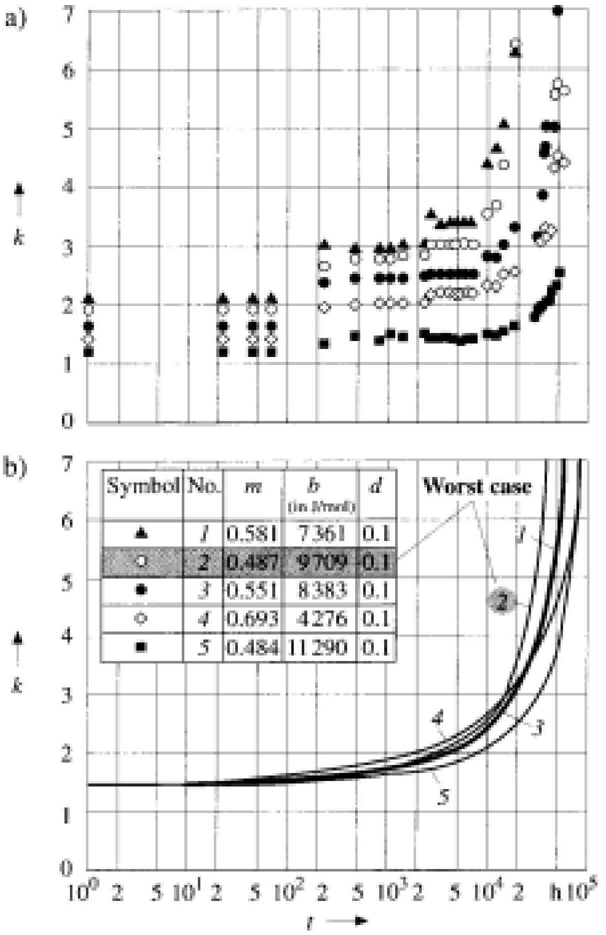
2 Evaluation of Long-Term Tests

2.1 Fundamentals

The ageing eq. (2) cannot be solved in a unity form. Therefore the differential equation has to be transferred into a difference equation. So the ageing behaviour can be calculated with:

$$k(t + \Delta t) = k(t) + \dot{k}(t; m, b, d)\, \Delta t. \qquad (3)$$

In eq. (3), only the parameters m, b, and d are unknown. These parameters have to be determined by long-term tests. The aim of the evaluation of long-term tests is to find one parameter-triple m, b and d which describes the ageing behaviour of a joint depending on the design and the load. It is known that the ageing process is subjected to a scatter. This means, that joints with the same start-off performance factor (after fitting) k_0 and the same load can have a different lifetime. Consequently each joint is described by a different parameter-triple (**Fig. 1**). Furthermore, each measured joint resistance is faulty. These faults influence the values m, b and d.



Symbol	No.	m	b (in J/mol)	d
▲	1	0.581	7361	0.1
○	2	0.487	9709	0.1
●	3	0.551	8383	0.1
◇	4	0.693	4276	0.1
■	5	0.484	11 290	0.1

Fig. 1. Determination of the joint with the fastest ageing (worst case), busbar joints in indoor air, temperature on the busbar $\vartheta_{\mathrm{Sdu}} = 150\,°\mathrm{C}$

a) Measured characteristics, joints with different initial performance factors

b) Calculated characteristics (eqs. (2) and (3)) with identical initial performance factor but different parameters m, b and d

To find such parameters m, b, and d which describe the ageing behaviour of electrical joints depending on design and load with higher sureness it is necessary to evaluate ten or more ageing courses. Some of these joints have to be in the phase of the accelerated ageing. Otherwise the experiments cannot be evaluated.

The evaluation is carried out in two steps. In the first step such parameters m, b and d with which all measured courses can be calculated best are determined. The calculation of the parameters is realized by the Newton-method. This parameter-triple describes the average ageing behaviour of the tested joint. The average lifetime of a joint is not so important for the reliability of the electrical power system. However, the lifetime of that joint which falls out first is very important. Because of the small number of tested joints with equal design, start-off performance factor and load mostly long-term tests cannot be analyzed statistically. Nevertheless, it is important to make reliable estimations about the minimal lifetime of a joint. Therefore the parameters m, b and d of this joint with the fastest ageing behaviour (worst case) have to be determined in the second part of the evaluation. For that, the parameter d which was gained in the first step is considered purpose as a constant. Only the parameters m and b of each joint have to be determined. Therefore, it is reached that the resulted worst-case-parameter-triple will be in the area of the average values. So it becomes possible to estimate the lifetime of joints with different load or start-off performance factors. Only the parameters m, b and d from joints which are in the phase of the accelerated ageing can be evaluated separately, because only these parameters describe joints courses clearly.

Mostly it is not possible to estimate the joint which has the fastest ageing behaviour by the measured values, because the tested joints differ from the load and start-off performance factor k_0. These joints can only be compared with their parameter-triple m, b and d. Therefore it is necessary to calculate the ageing course with the help of eq. (3) with the assumption that all joints have the same load, design and performance factor after assembling. The joint which reaches a given limiting value first represents the worst case (Fig. 1).

2.2 Aluminium-to-Aluminium Joints

Experiments on busbar joints with different current load were carried out, which caused a conductor temperature between 20 °C ($I = 0$ A) and 150 °C.

It can be observed that the ageing of aluminium-to-aluminium joints is characterized by a formation phase over 2000 h to 4000 h.

It is obvious that the ageing depends very strongly on the current loads. The higher the current and as a result the joint temperature is, the smaller is the lifetime of the joint. The evaluation of the tests shows that the worst-case parameters of experiments with different loads are of the same size. It shows that the ageing behaviour of aluminium-to-aluminium busbar joints is equal in a temperature range up to 150 °C.

Furthermore, no differences in the ageing behaviour between joints in indoor and outdoor air (city of Dresden) and transformer oil are observed. Therefore one worst-case-parameter-triple for all aluminium-to-aluminium busbar joints can be determined with

$$m = 0.487, \quad b = 9709\ \mathrm{J/mol}, \quad d = 0.1.$$

The ageing velocity depends on the start-off performance factor k_0 very strongly. The worse the assembling quality, the higher the performance factor k_0, the shorter the lifetime (Fig. 1). Small performance factors can be reached if the contact surface is cleaned well with a wire brush. The same effect can be reached if the contact surface is grooved. Therefore many parallel metal contact areas are developed. These joints are characterized by small performance factors k_0 with a small mean variation. Long-term tests have revealed that busbar joints with a grooved contact surface and a conductor temperature of 70 °C show no ageing after 90000 h of current load.

Partly contact pastes are used. The ageing behaviour of joints were tested with two different types of these pastes.

Joints with acid-free contact paste "A" have a somewhat higher performance factor k_0 and a nearly three times higher ageing velocity than joints without this contact paste ($m = 0.946$, $b = 6\,582$ J/mol, $d = 0.1$). Therefore the contact paste "A" is not suitable for busbar joints.

In contrast to that, the contact paste "B" has a different behaviour. This paste consists of 20 % acid-free contact paste and 80 % granules of zinc. The granules are very fine. Therefore this particles are laid round the constriction area like a pollution layer. These joints have a small start-off performance factor k_0 with a small mean variation and a very high ageing resistance. The contact paste "B" is recommendable for Al-to-Al busbar joints.

Furthermore, long-term test were carried out on busbar joints whose aluminium conductor material was alloyed with 0.7 % Fe and 0.5 % Mg. These joints show no ageing at a conductor temperature of $\vartheta_{\text{cdu}} = 100$ °C and a load period of 90 000 h. It is assumed that this higher ageing resistance has its roots in the higher mechanical strength (F17) and a smaller tendency to chemical reactions in comparison with pure aluminium (F7).

2.3 Aluminium-to-Copper Joints

The ageing behaviour of aluminium-to-copper joints is determined by chemical reactions and additionally by electrical and thermal migration processes at the constriction areas.

Al-to-Cu joints have no reveal formation phase. With some joints, the performance factor is somewhat smaller during the first hours. The reasons for that are the fretting and the reducing of the gap between the conductors through the flow of pollution layer and as a result of this the enlarge of the size and the number of metal contact areas [2–4]. Long-term tests show that Al-to-Cu joints age faster than Al-to-Al joints.

The ageing behaviour in indoor air and in transformer oil are identical (**Fig. 2**).

The evaluation of long-term tests resulted in the following worst-case parameters for Al-to-Cu joint in air and transformer oil:

$m = 0.441, \quad b = 17\,349$ J/mol, $\quad d = 5.$

With the help of the parameter-triple it is possible to compare the ageing behaviour of different materials. So the calculation of the lifetime of Al-to-Al and Al-to-Cu busbar joint with equal design, construction and load with the worst-case-parameter-triple for each joint material was done with eq. (3). The result of the calculation shows that Al-to-Al joints have nearly a twenty-times higher life expectation than Al-to-Cu joints (**Fig. 3**). Al-to-Cu joints are not recommendable for the power transmission system.

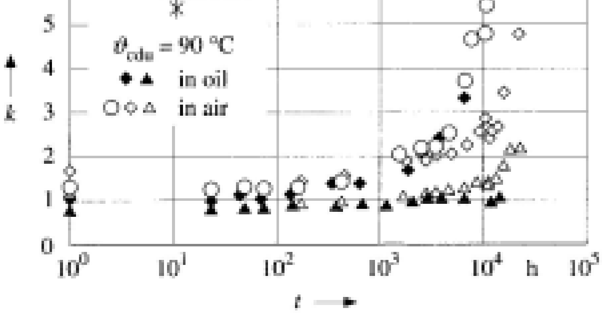


Fig. 2. Measured ageing behaviour of Al-to-Cu busbar joints in indoor air and transformer oil

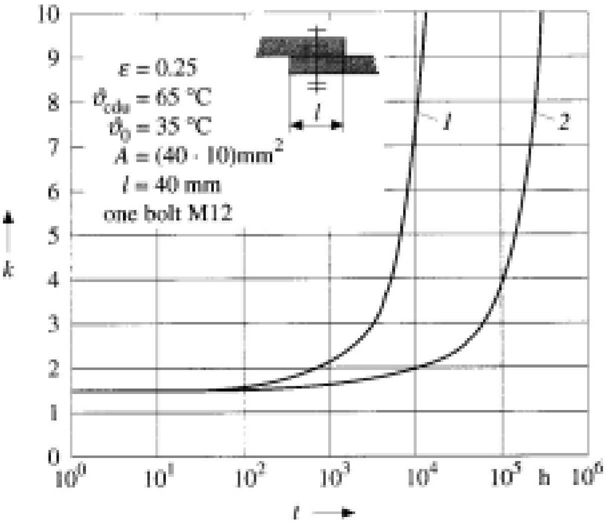


Fig. 3. Comparison of the ageing behaviour of busbar joint with different conductor materials but equal load by calculation (worst-case parameter m, b and d)
1: Al-to-Cu ($m = 0.441$; $b = 17\,349$ J/mol; $d = 5$)
2: Al-to-Al ($m = 0.487$; $b = 9\,709$ J/mol; $d = 0.1$)

3 Determination of a Limiting Performance Factor

Limiting values of the performance factor can be gained from different points of view depending on the operating conditions.

A limiting value can be that performance factor k_{m} if the melting temperature on the constriction are is reached. For all Al-to-Al joints which are included in the standard DIN [5, 6] these limiting performance factors k_{m} were calculated in indoor air with the help of the ageing eq. (3). The limiting performance factor k_{m} is not a constant value. It depends on the design and the load of the joint. But it can be said that the performance factor for Al-to-Al busbar joints which are loaded with nominal current should not be higher than $k_{\text{m}} = 7$. Joints with a bigger surface, for example clamps, can have smaller limiting values $k_{\text{m}} \approx 4$.

Due to the ageing of a joint the joint temperature can be so high that neighbouring insulating materials, such as Oil, PVC and PE, are destroyed. Depending on the permitted temperature of the insulation material and the current load, the limiting performance factor can also be calculated.

4 Parameters which Influence the Lifetime

With the help of ageing models the influence of several parameters on the lifetime can be estimated [7–9]. The possibilities which are offered by the ageing model are demonstrated on Al-to-Al joints.

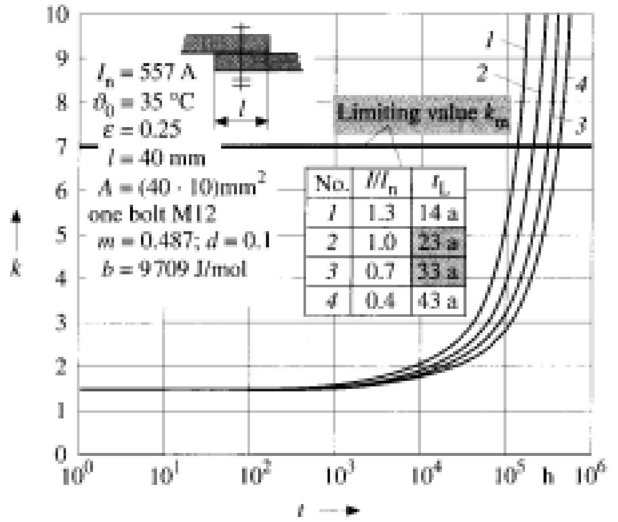


Fig. 4. Ageing behaviour of a Al-to-Al busbar joint in indoor air depending on the current (t_L: lifetime)

As the experiments showed, the current is one of the most important parameters of the lifetime. If the current is reduced from 100 % to 70 %, the lifetime increases from 23 a to 33 a (**Fig. 4**).

Furthermore, the ambient temperature influences the lifetime, too (**Fig. 5**). Consequently devices which are enclosed (ϑ_0 = 55 °C) have a considerably smaller lifetime than joints with the same current load in outdoor air (ϑ_0 = 15 °C) (16 a to 31 a).

The start-off performance factor k_0 has a major influence on the lifetime (**Fig. 6**). A small performance factor k_0 is necessary to guarantee a long and reliable lifetime.

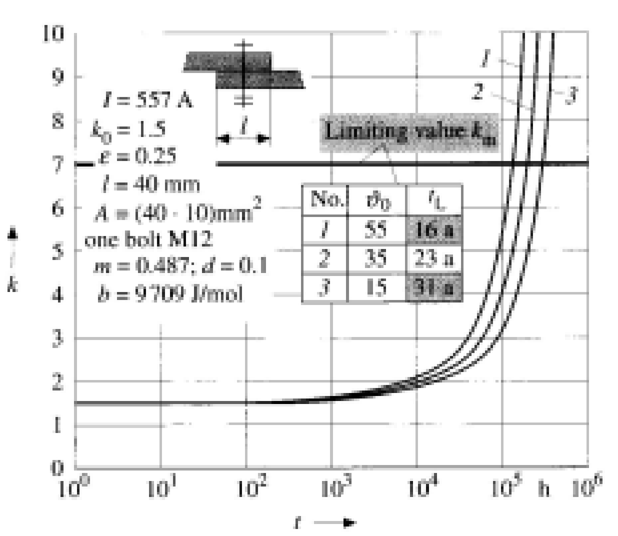


Fig. 5. Ageing behaviour of a Al-to-Al busbar joint in indoor air depending on the ambient temperature (t_L: lifetime)

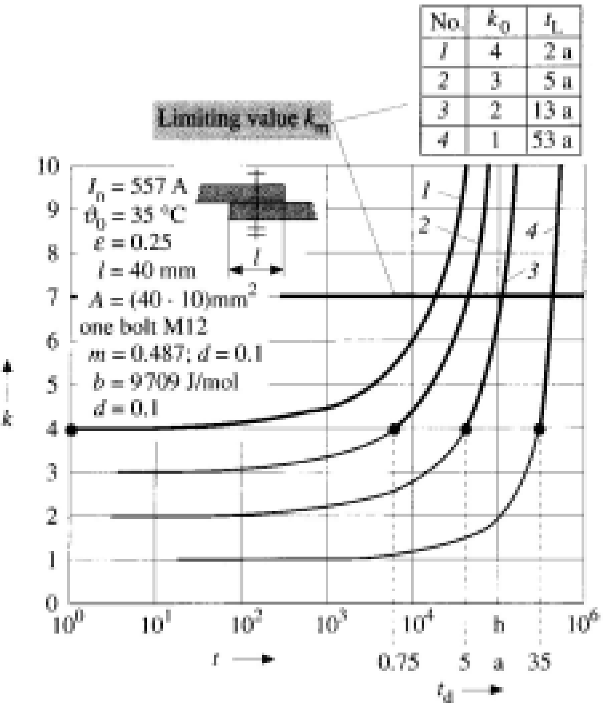


Fig. 6. Ageing behaviour of a busbar joint depending on the start-off performance factor k_0 (t_L: lifetime; (t_d: instant of diagnosis)

Unfortunately, not a single start-off performance factor k_0 can be given which guarantees the same lifetime for all joints. This is caused by the different ideal performance factors k_{id} of each joint. The pollution layer and the constriction resistance which can be estimated by the difference ($k - k_{id}$) are decisive for the ageing of an joint. If a joint with an ideal performance factor of e. g. $k_{id} = 0.7$ has a performance factor $k = 1.5$, the contribution of the pollution layer and the constriction resistant to the joint resistance amounts for 60 %. If an other joint with an ideal performance factor e. g. $k_{id} = 1.2$ has the same performance factor $k = 1.5$, the contribution of the pollution layer and constriction resistance to the joint resistance is 20 %. Although both joints have the same performance factor, the first joint ages faster. To guarantee a joint with a high and reliable lifetime the performance factor after assembly should be:

$$k_0 = 1.5\,k_{id}. \tag{4}$$

5 Estimation of the Remaining Lifetime

If the performance factor of a joint is diagnosed, it is important to evaluate or rather, to know the residual lifetime of this joint. So corrective maintenance can be planned in advance.

With the help of the ageing model it is possible to calculate the remaining lifetime depending on the present performance factor, the previous lifetime and the load in future. This is shown by one example (Fig. 6, **Tab. 1**).

No.	Present performance factor k	Instant of diagnosis (in a)	Residual lifetime (in a)
1	4	0	2
2		0.75	4.25
3		5	8
4		34	19

Tab. 1. Remaining lifetime of a joint depending on the previous load period (correspondingly to Fig. 6)

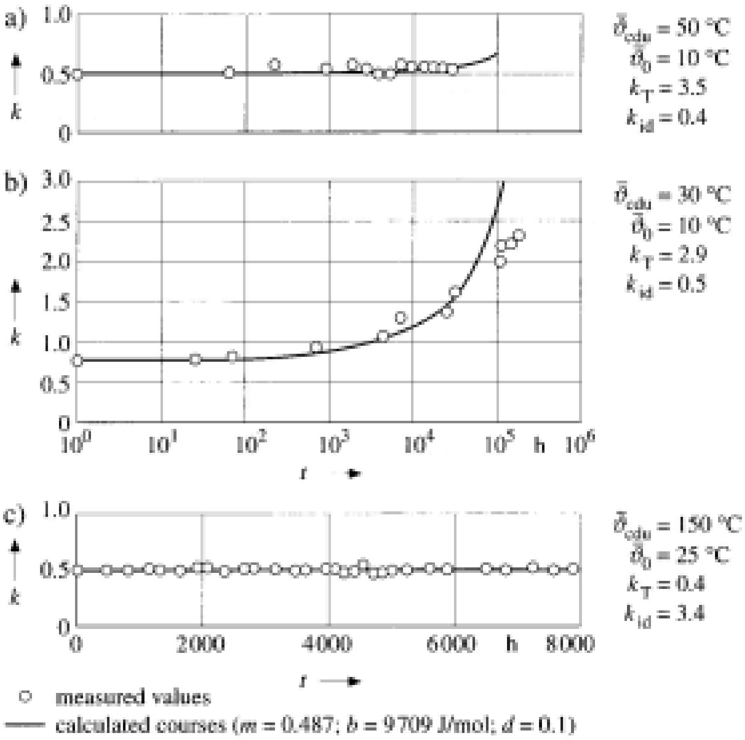


Fig. 7. Measured and calculated ageing behaviour of different joints
a) Bolted overhead line connection (outdoor) with an overhead line temperature of approximately 50 °C
b) Bolted overhead line connection (outdoor) with an overhead line temperature of approximately 30 °C
c) Pressed overhead line connection (outdoor) with an overhead line temperature of approximately 150 °C

If a performance factor $k = 4$ is measured after fitting the joint it will have a remaining lifetime of 2 a. If the same performance factor $k = 4$ is measured after 3/4 a, the remaining lifetime will be 4.25 a. This joint started with a performance factor $k_0 = 3$. Meanwhile a protection layer is round the constriction areas and the ageing process goes slower. If a performance factor $k = 4$ is determined after 34 a, the joint will have a further life expectancy of 19 a.

6 Transfer to Other Joint Types

The parameters m, b and d, which were gained on one joint type (busbar joint) can be also used on other constructions which have the same conductor material, the same ambient conditions and the same ageing mechanism (**Fig. 7**).

So the ageing behaviour of busbar joints which were fitted in a rectangular way could be simulated by calculation. Moreover, measured performance factor course of joints with overhead lines over 40.000 h which have a conductor temperature of 35 °C could be calculated with the parameters m, b and d of busbar joints.

7 Conclusions

The parameters m, b and d, which are important for the calculation of the performance factor characteristic with the mathematical ageing model [1, 2], were determined from long-term test on Al-to-Al and Al-to-Cu joints. As a result of the long-term tests it is possible to calculate the lifetime of the investigated conductor materials depending on the design and the load in transformer oil and air.

The ageing of joints is subjected to a mean variation. For the reliable operation of a device it is necessary to know the minimal lifetime of a joint. Therefore the parameters m, b and d of the joint which has the fastest ageing (worst case) have to be determined.

A very great influence on the lifetime of a joint has the conductor material. Al-to-Cu joints age nearly twenty-times faster than Al-to-Al joints with equal load.

Both experiments and calculations show that the quality of assembly decides about the lifetime significantly. Therefore it is recommended to develop such a fitting technology which effects small start-off performance factors k_0, e. g. grooved contact surface.

Furthermore, the current load and the temperature of the environment influences the ageing velocity. If the load, the conductor material and the start-off performance factor k_0 are in tune with each other, joints which have a lifetime over more than 50 a can be produced.

For the valuation of joints it is necessary to have limiting values. For joints in air such a limiting value can be the performance factor if the melting temperature is reached on the constriction area. This value k_m depends on the design and load of the joint. It can be calculated with the ageing equation.

The parameters m, b and d which were gained from busbar joints can also be used on other joint types if the same ageing is dominated by chemical reactions.

8 List of Symbols

A	surface
b	parameter
d	parameter
I_n	load current
k	performance factor
k_{id}	ideal performance factor
k_m	limiting value of performance factor
k_0	start-off performance factor
k_T	temperature equivalent performance factor
$\dot{k}$	velocity of contact ageing
l	length
m	exponent
R	gas constant
R_j	joint resistance
R_{ref}	reference resistance
T_s	temperature of the constriction area
t	time
t_d	instant of diagnosis
t_L	lifetime
Δt	time interval
ε	factor of emission

ϑ_{a} temperature of air/oil
ϑ_{cdr} temperature of conductor/busbar

References

[1] *Bergmann, R.; Löbl, H.; Böhme, H.; Großmann, S.:* Model to Describe the Chemical Ageing Behaviour of Electrical Busbar Joints. ETEP Eur. Trans. on Electr. Power 7 (1997) no. 5, pp. 345 – 350

[2] *Bergmann, R.:* Zum Langzeitverhalten des Widerstandes elektrischer Stromschienenverbindungen. Diss. TU Dresden/Germany, 1995

[3] *Braunovic, M.; Kharin, N.:* Dynamic processes in aluminum-to-copper bolted joints under current-cycling conditions. 16th Int. Conf. on Electr. Contacts (ICEC'92), Loughborough/UK 1992, Proc. pp. 241 – 247

[4] *Braunovic, M.:* Evaluation of different platings for aluminum-to-copper joints. IEEE Trans. on Components, Hybrids, and Manuf. Technol. (CHMT) (1992) no. 4, pp. 204 – 215

[5] DIN 43670/12.75: Stromschienen aus Aluminium, Bemessung für Dauerstrom. Berlin/Germany: Beuth, 1975

[6] DIN 43673 Teil 1/02.82: Stromschienen-Bohrungen und -Verschraubungen. Berlin/Germany: Beuth, 1982

[7] *Böhme, H.; Löbl, H.; Bergmann, R.:* Contact lifetime of joints in electrical power systems. CIGRE-Sympos. "Diagnostic and maintenance techniques". Berlin/Germany 1993, pap. no. 140-07

[8] *Großmann, S.; Löbl, H.; Böhme, H.:* Contact lifetime of joints in electrical power systems. 16th Int. Conf. on Electr. Contacts (ICEC'92), Loughborough/UK 1992, Proc. pp. 129 – 134

[9] *Böhme, H.; Löbl, H.:* Zur Theorie des Langzeitverhaltens von Aluminium-Stromschienenverbindungen. Elektrie 41 (1987) no. 5, pp. 179 – 183

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