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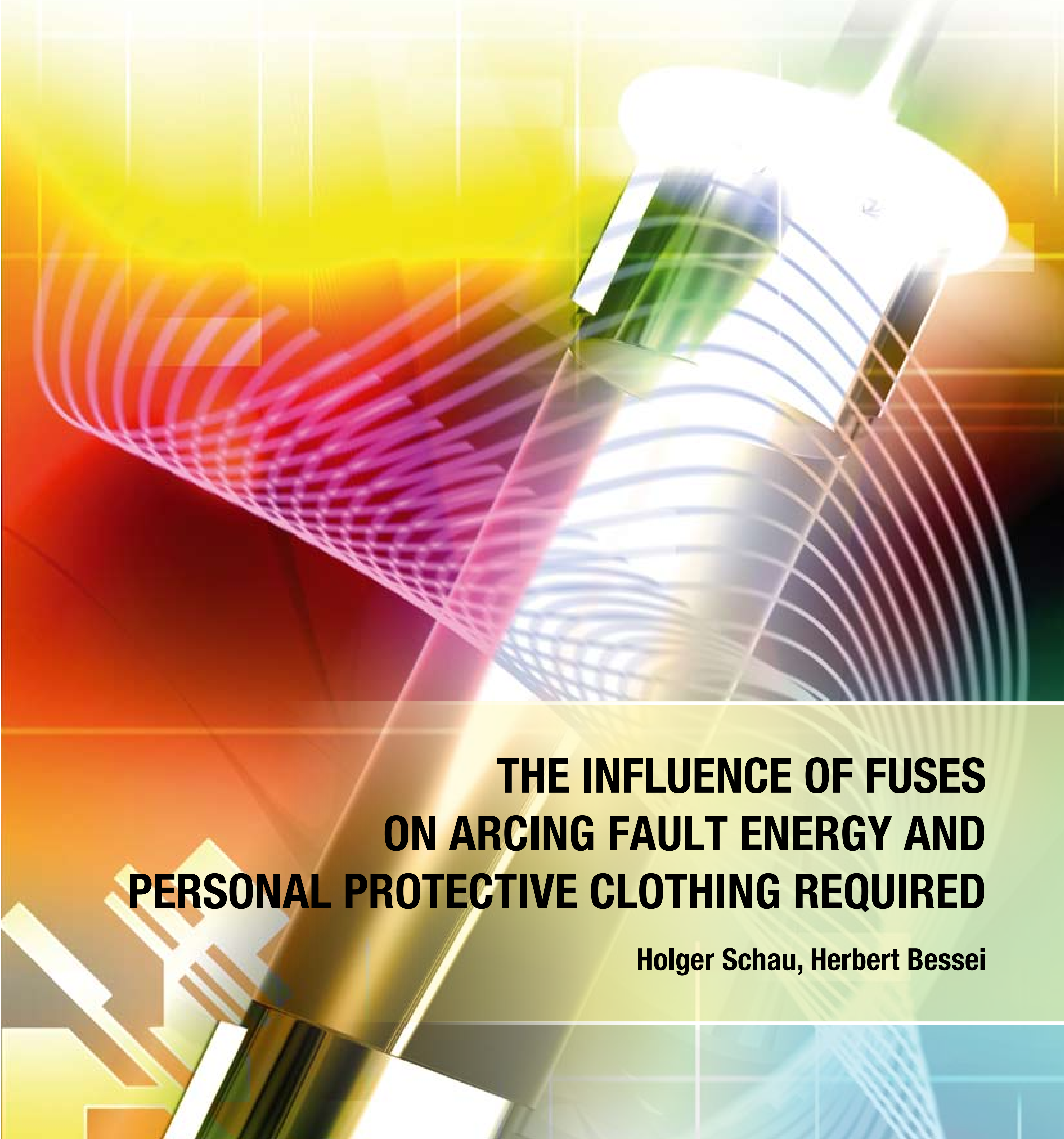

THE INFLUENCE OF FUSES ON ARCING FAULT ENERGY AND PERSONAL PROTECTIVE CLOTHING REQUIRED

Holger Schau, Herbert Bessei

The influence of fuses on arcing fault energy and personal protective clothing required

Holger Schau[1], Herbert Bessei[2]

[1] Technische Universität Ilmenau, POB 100565, D-98684 Ilmenau, Germany, holger.schau@tu-ilmenau.de
[2] fuseXpert, Geibstr. 27, D-55545 Bad Kreuznach, Germany, hbessei@fuseXpert.de

Abstract

The level of personal protection required against the thermal risks of electric fault arcs is influenced by the characteristics of the electrical protective devices as well as the protection level of the PPE, both aspects shall be co-ordinated. The electrical protective devices determine the utilization range of PPE. Fast-acting protective devices may significantly increase those ranges. Being proportional to the arcing fault energy, the thermal arc hazards are strongly influenced by the short-circuit duration. NH fuse-links, when correctly selected by also taking into account the current attenuation effect of the fault arcs, may reduce short short-circuit durations significantly.

Measurements and test were carried out in the high-power lab to evaluate the breaking characteristics of NH fuse-links in a LV short-circuit current path with fault arcs and the resulting thermal risks of fault arcs when controlled by the fuses. The incident energy resulting from the fault arcs is measured for this purpose. Conclusions are drawn on what protective clothing tested according to the box test (EN 61482-1-2) may provide adequate personal protection in dependency on prospective short-circuit current and fuse rating.

Keywords: LV arcing fault, fuses, fault duration, incident energy, personal protective equipment.

1. Introduction

The electric fault arcs occurring with short-circuit faults in electric power equipment and installations are enormous sources of power. There are particularly thermal effects (radiation and convective heat flux, metal splash) with high risks for persons especially in case of direct exposure, e.g. during live working or working in the vicinity of live parts.

From risk analysis [1] the hazards and effects of fault arcs are known to be mainly dependent on

- electric arc energy W_{arc},
- electric arc active power P_{arc},
- duration of arcing fault t_{arc},
- distance to the arc a.

The physical parameter characterizing the thermal effects at an exposed surface is the incident energy E_i. This is the density of the heat energy resulting from the heat flux in the distance a from the arc. The relationship between the electric arc energy and the incident energy is, however, very complex and sophisticated. The heat transmission function f_T is nonlinear and depends from a large variety of influences [1,2]:

$$E_{i0} = f_T \cdot W_{arc} \qquad (1)$$

The electric arc is a thermodynamic system showing a stochastic behavior with strong changes with time. It is not possible to derive a general transmission function. And it is also impossible to exactly calculate the incident energy on the base of a physical model.

The electric arc energy is determined by the arc active power and the arc duration. The electric arc active power depends on the conditions of the electric power system (short-circuit capacity of the system) and the power equipment construction. The arc duration is equal to the fault duration t_k and is determined by the clearing time of the network short-circuit protection devices (or special electric protective devices installed).

Consequently, personal protection can generally be achieved by limiting the exposure energy as well as the arc duration.

Tested personal protective equipment (PPE), mainly protective clothing, is the necessary preposition to prevent personal injury if there is the risk of direct arc exposure while working. The most important technical measure to protect persons consists, furthermore, in the use of suitable electrical short-circuit protective devices such as electrical fuses (e.g. NH fuse-links). If co-ordinated, PPE and electric protective devises may together essentially contribute to increase personal safety against electric fault arcs.

Measurements in the high-power lab have been carried out. The experimental investigations were made at the set-up and test system of the box test according to IEC or EN 61482-1-2, respectively, with installing fuses of different ratings in the electric test circuit and measuring the electric arc energy and incident energy. These tests enable in principle to draw conclusions on the limitation of the arc hazards by means of fuses.

2. Test set-up

All tests of the lab measurements described in this paper were performed according to EN 61482-1-2 [1]. The test facility includes the following elements:

- electrical test circuit and electrode assembly
- test box surrounding the electrodes,
- test plate with two calorimeters,
- measuring system,
- data acquisition system.

The electric test arc is fired between two vertical electrodes surrounded by a plaster box with a parabolic shape and a volume of 1.6 * 10^{-3} m^3. The box is open to one side. In front of this opening a test plate where the incident energy is measured is placed.

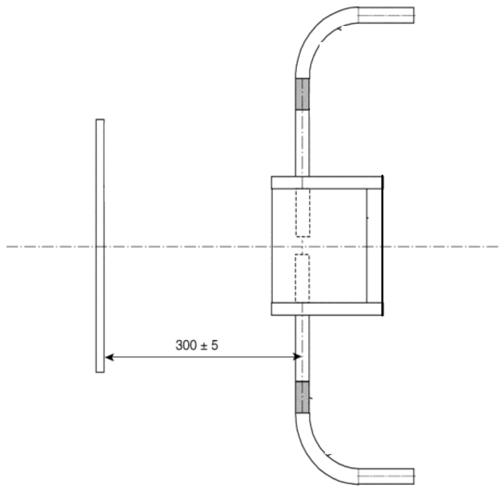

Fig.1: Principle set-up for arc tests

Fig. 1 shows the test box with electrodes and the power supply cables as well as the test plate. The distance between test box and test plate is exactly 300 mm.

The upper electrode consists of aluminum and the bottom electrode is made of copper, both with a diameter of 25 mm. The electrodes are arranged in a distance of 30 mm (electrode gap).

The test plate consists of an insulating and heat-resistant material. The test plate is centered to the arc and parallel to the perpendicular arc axis. Two copper calorimeters are mounted in the plate.

3. Electrical test parameters

The tests were performed in the high-power test laboratory supplied by a test transformer of 800 kVA.

The test voltage was 400 V AC (50 Hz). Tests were carried out in three series of different prospective test currents. The prospective short-circuit current (metallic short-circuit of electrodes) in the 2-phase circuit was set to values of 2.3, 4 and 7 kA. Metallic short-circuit tests as well as arc tests were performed. The test circuit impedance ratio R/X is shown in Tab. 1.

Tab.1: R/X ratio of the test circuit impedance

Test current	R/X
2.3 kA	0.21
4.0 kA	0.44 and 0.55
7.0 kA	0.56

Tests were started by switching-on the test circuit by a contactor. The test arcs were fired by means of a fuse wire. The fuse installed in the test circuit broke the test circuit. In those cases the test duration (current flow) was not interrupted by the fuse after 1 s a test circuit breaker switched-off the circuit.

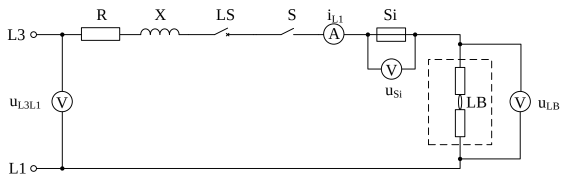

Fig. 2: Electric test circuit

Fig. 2 shows the test circuit. The abbreviations stand for:

L3, L1	phase 3, phase 1,
R	resistance,
X	reactance,
LS	circuit breaker,
S	contactor,
Si	fuse,
LB	arc (simulated fault arc).

The data acquisition system recorded the phase-to-phase voltage (u_{L3L1}) of the test circuit, the actual test current (i_{L1}), the arc voltage (u_{LB}), the fuse voltage (u_{Si}), and the temperature rise curves of the two calorimeters. In the arc tests the test current recorded is the arc current.

The fuses installed in the test circuit were NH fuses 500 V AC (NH00, NH1, NH2, NH3). Fuses with various ratings (100 A to 500 A) and different operational characteristics (utilization ranges: general purpose gG, and ultra-fast characteristic aR) were used. The majority of tests was performed with the general purpose NH fuses for line protection. In a limited number so-called “work protective fuses” with ultra-fast characteristic were investigated.

Fuses of different manufacturers were used.

4. Test program

As mentioned above, the test program was separated in three different test series. Each test series differs from the other one by the prospective short-circuit current of the test circuit. First a short-circuit current of 2.3 kA was set. In this series fuses with rated currents (fuse ratings) of 100 A up to 315 A were tested. The second series included fuses of 100 A up to 400 A with a short-circuit current of 4 kA. In the third series fuses of 200 A up to 500 A were used, the short-circuit current was 7 kA.

At the beginning of each series the short-circuit current, which was available, was measured by shorting the electrical circuit. Then fuses of the each rating selected were tested three times: first the test was carried out for bolted fault (without any fault arc), and then twice with fault arc.

In the following, the test current is always indicated as r.m.s. value of the bolted prospective current. The actual current flowing in the fault arc tests is named as arc current.

5. Measurement evaluation

As a first step the measured values were evaluated to identify electrical arc energy. A quantification of arc energy was achieved by measuring arc current and arc voltage. With the knowledge of operating time (t_{op}) the arc power is to be calculated:

$$W_{arc} = \int_0^{t_{op}} p_{arc}\, dt = P_{arc} \cdot t_{op}\,. \qquad (1)$$

The incident energy can be calculated from the temperature rise curves of the calorimeters using the following equation:

$$E_{i0} = K \cdot dT_{\max}\,. \qquad (2)$$

Because the calorimeters are directly exposed to the arc this is the direct exposure incident energy E_{i0}. K is the calorimeter constant. It is the product of the mass and specific heat of the calorimeter copper plate divided by its cross-sectional area. It has to be multiplied by the maximum temperature rise measured (delta peak temperature) dT_{max} during the arc test observation time of 30 s.

The evaluation of the incident energy is based, according to the box test procedure, on the Stoll limits for the onset of second degree skin burns [4]. The corresponding Stoll value is found by means of the Stoll constant S = 50.204 kW/m^2 and the time t_{max} when the delta peak temperature is reached (time to delta peak temperature) with the equation:

$$E_{i\ Stoll} = S \cdot t_{\max}^{0,2901} \qquad (3)$$

The time to delta peak temperature is in a range of about 4…10 s under the energy conditions studied.

The comparison of the incident energy measured and the Stoll value gives the conclusion about second-degree burns. If the measured value is above the Stoll value, second-degree skin burns may occur. For this estimation always the larger incident energy value measured by the two calorimeters was used.

According to IEC 61482-1-2 in PPE testing there are two test or protection classes, class 1 and class 2. The PPE tests are to prove if PPE protect persons under the test exposure conditions by being thermal arc resistant and preventing incident energies causing 2nd degree burns (transmitted incident energies may not exceed Stoll limits). The Stoll curve is not exceeded if PPE of the according class are used. The classes are characterized by the energy levels according to Tab. 2.

Tab. 2: Box test protection levels

class	E_{i0} in kJ/m^2	W_{arc} in kJ
1	135	158
2	423	318

The class energy values characterize the energy levels up to which PPE provide protection against the thermal hazards of fault arcs. These levels are used for assessing if the arc energies resulting in case of fault interruption by a fuse exceed the protection level of PPE.

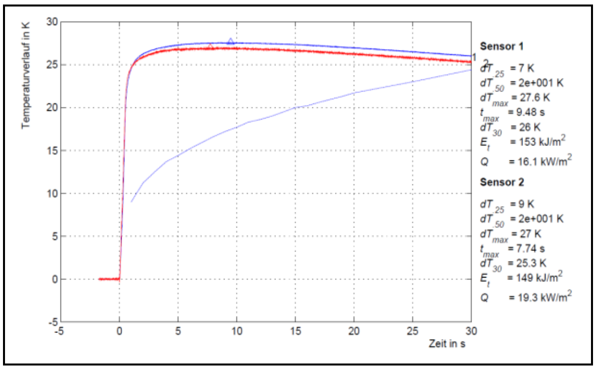

Fig. 3: Temperature rise curves of the two calorimeters measured for an example

Fig. 3 shows the temperature rise curves of the two calorimeters measured for the example of an arcing fault with a prospective short-circuit current of 4 kA interrupted by a 315 A gG fuse. The delta peak temperatures are marked in the curves. In addition the Stoll limit curve is also presented in this figure in form of a transformed temperature-time curve illustrating that the Stoll limit is exceeded significantly in this case. The incident energy (highest value) is 153 kJ/m², meaning that personal protection is not given for PPE class 1 but would be provided by using class 2 PPE.

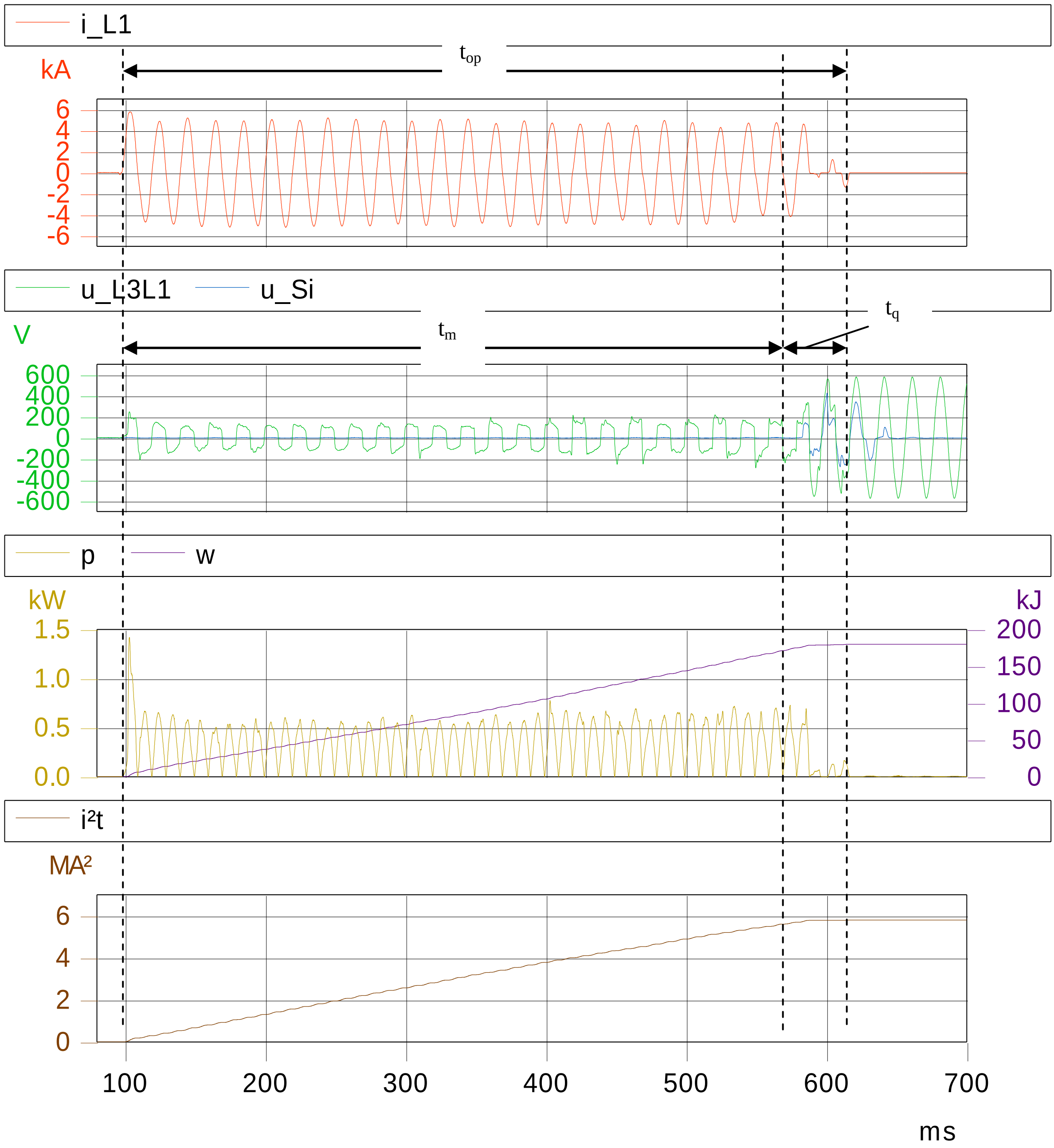

Fig. 4: Oscillograms of the electrical parameters of a test example (test current 4 kA, fuse NH2 gG rating 315 A)

The oscillograms of arc current, arc voltage and fuse voltage for this example are shown in Fig. 4. Furthermore the arc power (instantaneous values p), the electric arc energy and the operational integral of the fuse (MA^2s) are presented. This fuse integral i^2*t is calculated for all tests, too.

The arc energy over the interval of test arc existence is about 180 kJ. The same conclusion (as found before on the base of the incident energy consideration) results from this value: class 1 PPE does not provide personal protection but class 2 PPE will do it.

The energy values are connected with the operation time (t_{op}) of the fuse (fusing time). The operating or fusing time t_{op} consists of the melting (or pre-arcing) time (t_m) and fuse arcing time (t_q). The fuse arcing time is that time which is necessary to extinguish the switching arc within the fuse cartridge. The time periods are marked in Fig. 4. In the example there is a fusing time of 575.1 ms. The melting time is 487.1 s and the fuse arcing time is 88 ms. The fusing time is equal to the arc duration t_{arc} and presents also the short-circuit duration t_k.

The ratio of the prospective fault current to the fuse rated current is 12.7. The arc current in the test being 3.34 kA, a ratio arc current to fuse rating of 10.6 results.

6. Measurement results

6.1. General breaking behavior

The breaking behavior is generally characterized by scattering. In the arc test the fault arc current determines the breaking process. The arc tests are repeated twice for each test setting, always the longer fusing time and greater energy values were selected as the according test result. So results are on the safe side.

Depending on the ratio between the test current and the fuse rating, the fuses show current-limiting breaking or non-current-limiting breaking. In the example in Fig. 4 the latter one is given.

Current-limiting breaking is characterized by a very fast fuse operation in case of large current. The fusing time (operating time) is shorter than a current half-cycle, the current does, as a rule, not reach its prospective peak value. The fuse switching arc limits the let-through current. The operational time is not only dependent on the current but also on a variety of other parameters such as switching angle, impedance ratio R/X etc. Regarding the fusing time, the fuse behavior is in a “chaotic range” [5], meaning that there is no clear defined function or tendency. The fuse behavior is characterized by its melting integral (pre-arcing), the time values given in the fuse characteristic are so-called “virtual” operating times that are not equal to the real operating times.

In those cases the fault arc energy as well as the thermal incident energy resulting is in general very small because of the short fusing times being below about 10 ms. The current-limiting range has no practical importance what will be shown by the following estimations, too.

Work at opened switchgear or live working is usually practiced up to a range of the prospective 3-phase short-circuit current of about 25 kA. The short-circuit current in the L.V. main distribution of a 630 kVA transformer is about 22.5 kA maximum. In a 400 V system the normalized arc power k_P is about 0.38 (for the R/X of 0.2) according to [2]. For the maximum power system short-circuit capacity

$$S_k'' = \sqrt{3} \cdot 0.4 \text{ kV} \cdot 22.5 \text{ kA} = 15.588 \text{ MVA}$$

resulting from the current range up to 22.5 kA and the short-circuit duration t_k (according to the fusing time) of 10 ms, the electric arc energy is only

$$W_{arc} = k_P \cdot S_k'' \cdot t_k = 0.38 \cdot 15.588 \text{ MVA} \cdot 10 \text{ ms}$$
$$W_{arc} = 59.2 \text{ kJ}$$

to be expected in case of a 3-phase arcing fault. The incident energy will not be larger than 78.7 kJ/m^2 (using the maximum box test ratio between incident energy and electric arc energy of 1.33 according to Tab. 2 as worst case estimation). The real arc energy and incident energy values will be (under circumstances significantly) smaller in most practical fault scenarios.

The Stoll limit resulting for a time to delta peak temperature of 4 s is 75.1 kJ/m^2, for 5 s it is 80.1 kJ/m^2. In most practical cases time to delta peak temperature is longer, leading to higher Stoll limits. That means that the Stoll limit will not be exceeded and there is no risk of second degree skin burns if there is a current-limiting fuse breaking behavior. In addition the energy values are far below the energy limits of class 1 PPE.

In the arc test carried out with current-limiting fuse interruptions the arc energy was in a range of only about 2…14 kJ. The incident energies ranged between 2.5 and 11.7 kJ/m^2.

For these reasons mentioned before the current-limiting fuse operation can stay and will be out of consideration in the following.

The test series have shown that a current-limiting fuse behavior was given under arcing fault conditions if the ratios of the prospective (bolted) fault current to the fuse rating current $I_P/I_{nSi} = I''_k/I_{nSi}$ was higher than 20…25 for general purpose fuses (utilization category gG). In case of very fast-acting characteristic fuses (aR) a ratio $I''_k/I_{nSi} > 8…10$ is necessary to obtain a current-limiting fuse behavior.

In practical applications as so-called "working protective fuses" which are temporarily installed during live working activities take place in power equipment, often NH aR fuses with ratings of 160 A to 250 A are used. Consequently the current-limiting behavior may be expected in case of arcing faults if the prospective short-circuit currents at the working places are higher than 1.3 to 2 kA what is given in most practical scenarios.

NH fuse links operating current-limiting provide personal protection by preventing arc durations causing thermal risks. Higher arc energy and incident energy levels result from longer arc durations which are resulting from a non-current-limiting behavior. These conditions have to be considered mainly in the following.

6.2. Operating times

In the Fig. 5 to 10 essential analysis results of the measurements are summarized. These figures show the fusing times, arc energies and incident energies measured in the arc tests for non-current-limiting fuse behavior. All results refer to NH fuses of the utilization category gG (general purpose fuses).

The measurement results are supplemented by extrapolations, made on the base of tendencies obtained in connection with fuse t-I characteristics, to draw conclusions on protection ranges.

Fig. 5 shows the fuse operating times t_{OP} measured in the 3 series of different prospective short-circuit currents in the arcing fault tests. The parameter is the fuse rating I_{nSi}.

Regarding fusing times also bolted faults are considered.

The fusing time depends mainly on the actual fault current flowing in the electric circuit. This current is strongly influenced by fault arc conditions. There is a current attenuation resulting from the nonlinear fault arc resistance. In the test series the current attenuation factor was between 0.78 and 0.87 (average 0.85) according to the test set-up (particularly the electrode gap of 30 mm). In general the current attenuation is dependent on different factors [2].

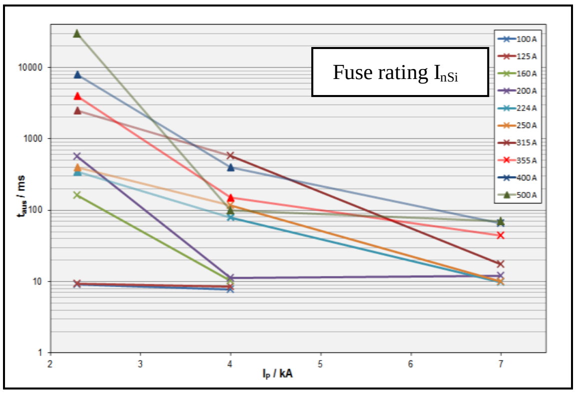

Fig. 5: Fuse operating times versus prospective short-circuit current for arcing faults (x –measured, Δ – extrapolated), gG fuses

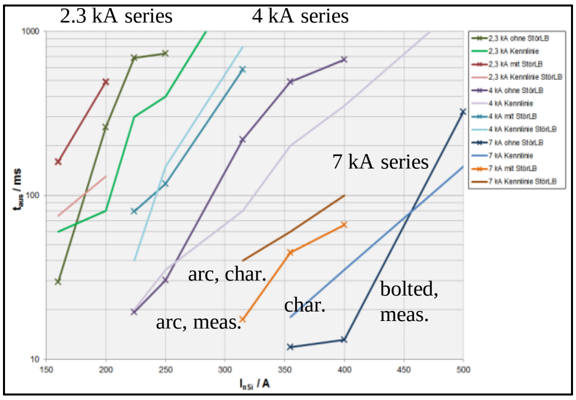

Fig. 6: Comparison of the fuse operation times for bolted faults and arcing faults measured in the 3 test series with the values obtained from the characteristics, gG fuses

Consequently the fuse operating times are longer in case of arcing fault tests than those of bolted short-circuit tests. The determination of the fuse operating time for arcing faults has to be based on the actual fault arc current. Because the arc resistance varies stochastically the actual current attenuation or arcing fault current cannot be predicted exactly. Fusing time determination based on bolted short-circuit currents generally result in a considerable inaccuracy.

Measurement results show also deviations to the theoretical operating times according to fuse current-time characteristics. In Fig. 6 the fuse operating times measured in the 3 test series for bolted as well as arcing faults are shown in separate curves as well as the values obtained from the fuse characteristics by means of the bolted fault current and the actual arc current measured (theoretical values). The curves connect the values for the different fuse rating currents. The first 4 curves belong to the 2.3 kA series, the second 4 curves to the 4 kA series, and the last 4 curves to the 7 kA test series with different fuse ratings. The curves of the values measured are marked by crosses, the curves without marking result from the characteristics. The curves for bolted faults show the shorter operating times and are, consequently, left of those of the arcing faults.

6.3 Arc energy

In Fig. 7 the electrical arc energy is shown as a function of the prospective short-circuit current. A curve is plotted for each fuse rating.

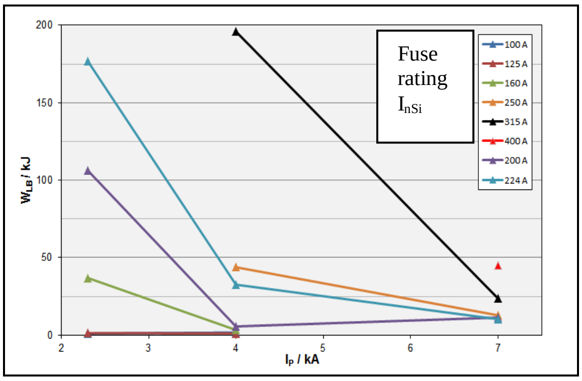

Fig. 7: Electric arc power measured in the test series in dependency on the prospective short-circuit current, gG fuses

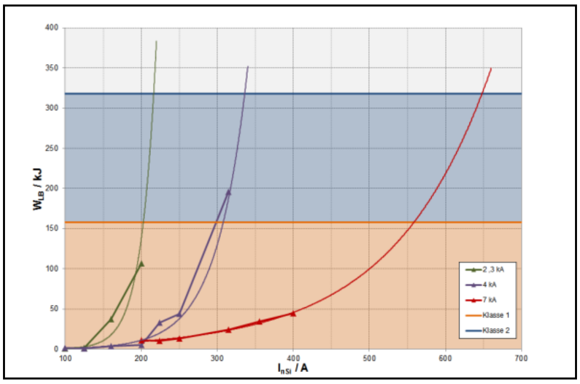

Fig. 8: Electric arc energy to be expected in dependency on NH fuse rating (measured values and extrapolation functions for the different short-circuit currents), gG fuses

The arc energy is the higher the larger the fuse rating is, and the smaller the prospective short-circuit current is. The arc energy increases when the ratio between prospective short-circuit current and fuse rating current becomes smaller. The critical cases from the protection point of view are small ratios I''_k/I_{nSi}. Main reason is the increase of the arc duration (fuse operating time) with decreasing fault current for a given fuse rating.

In Fig. 8 the arc energy is shown in dependency on the fuse rated current. For each individual short-circuit current a curve is plotted. The electrical arc energy increases with rated current as found before.

The measurements were supplemented by extrapolation curves derived from regression functions and estimations based on fuse characteristics and fusing times expected for attenuated fault currents. In the figure, furthermore, the protection ranges of PPE are marked. The red range indicates the protection by PPE class 1, the blue one the range of PPE class 2. It can be concluded up to which fuse rating personal protection is given by the fuse in combination with class 1 or class 2 PPE for the according prospective short circuit current. For instance, with a prospective short-circuit current of 4 kA and a fuse rating of 315 A there is protection with class 2 PPE (see example in Par. 5), with a 355 A fuse the protection does not more exist. As another example, for prospective short-circuit currents higher than 7 kA personal protection against the thermal hazards of electric fault arcs can be assumed as long as the fuse rating is 500 A or lower when using PPE of class 1, and not higher than 630 A when using PPE class 2.

6.4 Incident energy

Fig. 9 shows the incident energy measured for the 3 prospective short-circuit currents with the different fuse ratings. There are generally the same relationships as found before in case of the arc energy.

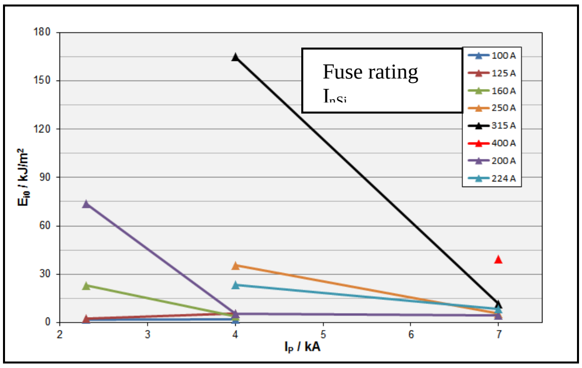

Fig. 9: Incident energy in the test series in dependency on the prospective short-circuit current, gG fuses

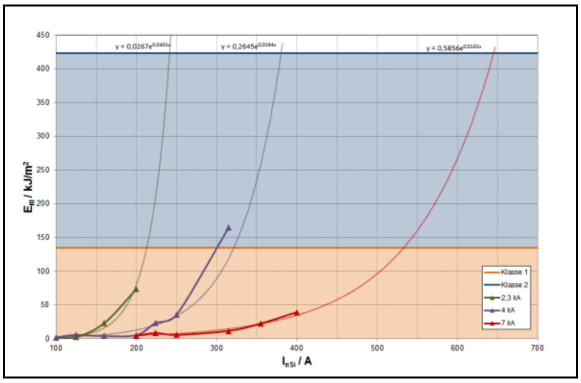

Fig. 10: Incident energy to be expected in dependency on NH fuse rating (measured values and extrapolation functions for the different short-circuit currents), gG fuses

In Fig. 10 the incident energy is shown as a function of the fuse rated current. Each of the individual short-circuit currents analyzed are represented by a curve. The curves are similar to the curves of Fig. 8 for the arc energy, too.

Regarding the conclusions for the protection ranges resulting from the application of the fuse ratings, the limits found on the base of the arc energy are also confirmed by the consideration of the incident energy.

7. Summary of test results

Table 3 presents a summary of the results achieved. It shows the fuse ratings up to which personal protection against the thermal hazards of an electric fault arc will be provided in combination with PPE of class 1 or class 2. The green colored range (marked by "+") characterizes the combinations where protection is given. In those cases where the measurement results are close to the limits a categorization on the "safe side" was chosen. The results are valid for general purpose fuses (gG).

According to the tests in which 3 levels of the short-circuit current are adjusted, the application of the results has to made so that each line of the table is valid for a prospective short-circuit current equal or larger than the value indicated (minimum short-circuit current. It is useful to supplement the investigations by measurements for other levels of prospective short-circuit currents, too. For a given short-circuit current the protection situation may be improved by using a smaller fuse rating. The protection range limit is described by the maximum fuse rating.

The results of Tab. 3 are valid for 2-phase short-circuits. The energy levels measured result from a 2-phase fault arc. In case of 3-phase arcing the electric arc energy and the incident energy are higher. Consequently the protection limits are displaced.

Tab. 3: Protection ranges resulting from the use of NH gG fuses and PPE (2-phase arcing faults)

Prospective short-circuit current	PPE box test class	NH fuses gG AC: fuse rating I_{nSi} in A									
		NH 00			NH 1			NH 2			NH3
		100	125	160	200	224	250	315	355	400	500
2.3 kA	Class 1	+	+	+	+	-	-	-	-	-	-
	Class 2	+	+	+	+	+	-	-	-	-	-
4 kA	Class 1	+	+	+	+	+	+	-	-	-	-
	Class 2	+	+	+	+	+	+	+	+	-	-
7 kA	Class 1	+	+	+	+	+	+	+	+	+	+
	Class 2	+	+	+	+	+	+	+	+	+	+

8. Conclusions

The paper considers the use of NH fuses for reducing thermal hazards of LV fault arcs. For measurements the test set-up and a corresponding test program are introduced. The evaluation of measurement data covers the main parameters determining the protection needs, such as arc duration, electrical arc energy and incident energy. The protection aim is the prevention of 2nd degree skin burns (Stoll limits) without a thermal destruction of the necessary PPE.

The results show that NH fuses are able to limit the thermal arc hazards. If the fuses operate current-limiting, the arc duration is normally reduced to a degree where the resulting arc energy and incident energy does not inadmissibly harm the workers. The current-limiting behavior is given if the ratio between prospective short-circuit current and fuse rating current will be higher than 20…25 for general purpose fuses (utilization category gG). It is also generally provided by very fast-acting or ultra-fast acting NH fuses with ratings of 100…250 A that are used as “work protective fuses”.

Fuses are also able to protect persons when there is a non-current-limiting operation. In case of working activities connected with the possibility for the worker to become directly exposed to fault arcs generally PPE shall be used. PPE tested according to the box test is classified in one of two possible protection levels. Class 1 is the lower protection level and has to be seen as basic protection. For this, the combination of NH fuses and PPE was investigated.

The measurements were particularly concentrated to the current ratios where a current-limiting fuse behavior is not to be expected.

Both arc energy values measured and incident energy ones measured lead to the same protection conclusions (hazards as well as PPE necessary). It is sufficient to consider one of these parameters. From the practical point of view this is the electric arc energy. This parameter is also used for risk analyses and assessment.

The measurement results confirm the theoretical knowledge that the arc energy and incident energy show a falling tendency with growing prospective fault current. The assumption that the arc hazards are proportional to I^2t is not correct in case of fuses. Besides of the prospective short-circuit current at the fault place the rating of the upstream fuse is of first importance for the selection of PPE suitable.

Large arc durations as the result of long fusing times, particularly of more than 1 s, are generally critical. In most of these cases the protection levels of PPE can be exceeded.

Some of the conclusions of the protection by NH fuses were based on extrapolations. It is necessary to confirm these results by measurements, too. The aim for further work to do is to find out the exact limits where a protection by means of class 2 PPE is exceeded. It is necessary to extend test durations.

With the same regard other levels of the prospective short-circuit currents shall be investigated in order to both, reducing the steps between levels measured and extending the short-circuit current range. Regarding the latter aspect, NH fuses of higher ratings (including also transformer fuses gTr) should be used.

Main points for further investigations are measurements of 3-phase faults and the experimental confirmation of transformation considerations. These first analyses were focussed mainly on the test circuit conditions used in the standardized box test of PPE. The measurements are to be extended to 3-phase short-circuits (3-phase test circuits and arcing faults).

If there is a three-phase arcing fault the fuse operating time measured will be connected with arc energies that are, depending on the arc fault characteristics, 1.5 to 3 times as much as those determined under the 2-phase arcing conditions. Thus the protection limits will differ accordingly. This has to be proved experimentally by test series.

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