Co-ordination of LV Fuses and PPE for Personal Protection against the Thermal Hazards of Electric Fault Arcs

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Keywords: personal protection, electric fault arcs, thermal hazards, PPE, LV fuses

Principles of reducing arc hazards

Personal working at electric power equipment, particularly in case of live working or working near to live parts, has reliably to be protected against the hazards due to electric fault arcs. Main risk is the arc thermal exposure, and personal protection is, in accordance with the internationally-agreed point of view and recent standards, considered to be achieved when 2nd degree skin burns are prevented. The risk of skin burns depends on the heat density at the exposed area (directly or behind protecting equipment). This so-called incident energy is determined by the electric arc energy converted and partially transferred as heat, depending on the transmission conditions and the exposure distance to the arc as source.

Personal protection requires, in addition to technical and organizational measures, the use of Personal Protective Equipment (PPE) tested and certified against the thermal hazards of fault arcs. There is a certain energetic protection level of PPE based on the test level. The electrical protective devices existing or used in the system determine the clearing time of an arcing fault, and consequently the arc energy to be expected. Factors determining whether or what degree of personal protection is achieved are mainly the protection level of PPE and the characteristics of the protective devices, both aspects have to be coordinated for an efficient protection of personal.

One of the internationally harmonized PPE test standards is the Box Test according to IEC/EN 61482-1-2 [1] which has to be applied in Europe if conformity with the EC PPE Directive is claimed. This test can be carried out with one of two possible test energy levels: protection class 1 as a basic protection degree or class 2 as an increased protection level. There are user guidelines giving guidance what protection class has to be selected for the specific working activity and work place [2,3].

An important factor when selecting the proper PPE is the clearing time of the short-circuit protection devices in the system, power fuses may be very efficient means in LV power systems. The fuse operation is in general determined by the operating time-current characteristic. The fuse operation is dependent on the short-circuit current actually flowing in the short-circuit path and being attenuated in terms of the prospective short-circuit current (which flows in case of bolted fault) in a manner that can only roughly be approximated and predicted in LV systems. Wrong information is received when basing the determination of the fuse operation time on the bolted current that is usually derived from short–circuit current calculations (time too short, arc energy too low) [4]. The coordination of PPE and fuse selection requires carrying out measurements for checking and drawing safe conclusions for the degree of personal protection.

The arc energy converted increases with the clearing time. This relationship was found to be approximately linear. For a certain arc power, the longer the clearing time of the protective device, the higher the amount of arc energy released is. Consequently there is an "inverse" relationship between arc energy and short-circuit current level. Caused by the fuse operation characteristic, as the result, the arc energies can be higher with small fault currents (and low arc power) than with big ones. In case of big short-circuit currents there is a fast switching-off by the fuse, limiting the arc energy.

Laboratory measurements

In systematic laboratory measurements cut-off of 2-phase arcing faults and 3-phase ones in 400 V systems by means of LV fuse links (NH fuses) was analyzed in a short-circuit current range of 1…10 kA (prospective or bolted current). NH fuses 400 V and 500 V AC of various operation characteristics and rated currents were used for interrupting the test circuit:

- NH gG line fuses, ratings 50 A … 800 A
- NH gTr transformer fuses, ratings 250 kVA … 630 kVA
- NH ultrafast work-protecting fuses, ratings 100 A … 500 A.

Fuses of different manufacturers were applied. Aim was to find out under which fuse conditions the remaining thermal arc hazards are limited to a degree where personal protection is guaranteed by using PPE class 1 or class 2 for work at the according electric power equipment. Personal protection is given when PPE protection levels are not exceeded. This means that second degree skin burns are prevented, and the PPE is thermal resistant and stays functional. In test series the electric arc energy and thermal incident energy have been measured in dependency on the prospective short-circuit currents and the ratings of the fuse link, and correlated to the PPE protection classes.

Results of 2-phase arc tests with NH fuses

The 2-phase test series were carried out in the 400 V AC test circuit (50 Hz) and set-up of the box test standardized in IEC/EN 61482-1-2 [1]. The test arc is fired between two opposing vertically arranged electrodes (top: aluminum, bottom: copper, gap d = 30 mm) which are surrounded by a plaster box. In front of the open side of the box there is a test plate with calorimeters for measuring the direct exposure incident energy in a distance of a = 300 mm to the axis through the electrodes (arc axis, see Fig.1). The test currents were adjusted by means of series elements R and X with a ratio R/X ranging between 0.2 and 0.6 being typically for LV systems. Details of the test arrangement and first important results are already presented in [4,5].

In the arc tests the arc energy and incident energy appearing when the arc duration is limited due to cut-off of the circuit by a certain NH fuse were measured. Arc tests were repeated several times for determining mean values for each parameter setting. For final conclusion, the values of arc energy and incident energy measured were compared with the test levels of PPE according to the Box Test [1], and the parameters for keeping these limits were determined. Under standard exposure conditions (working distance a = 300 mm and directed exposure due to opened equipment of small inner volume characterized by equipment transmission factor k_T = 1 [3]) the test level is identical with the PPE protection level.

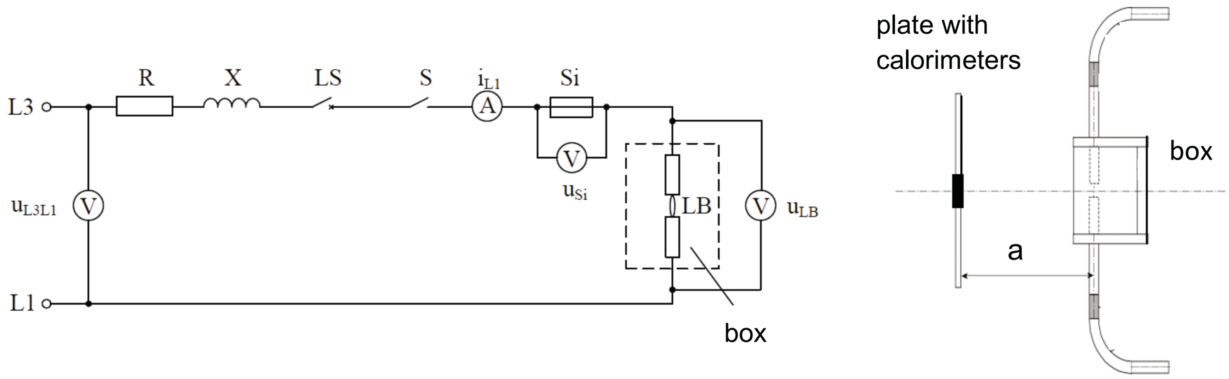


Fig. 1: 2-phase test circuit (left, with LS – breaker, S – contactor, Si – NH fuse, LB - arc) and electrode configuration with box and calorimeters (right)

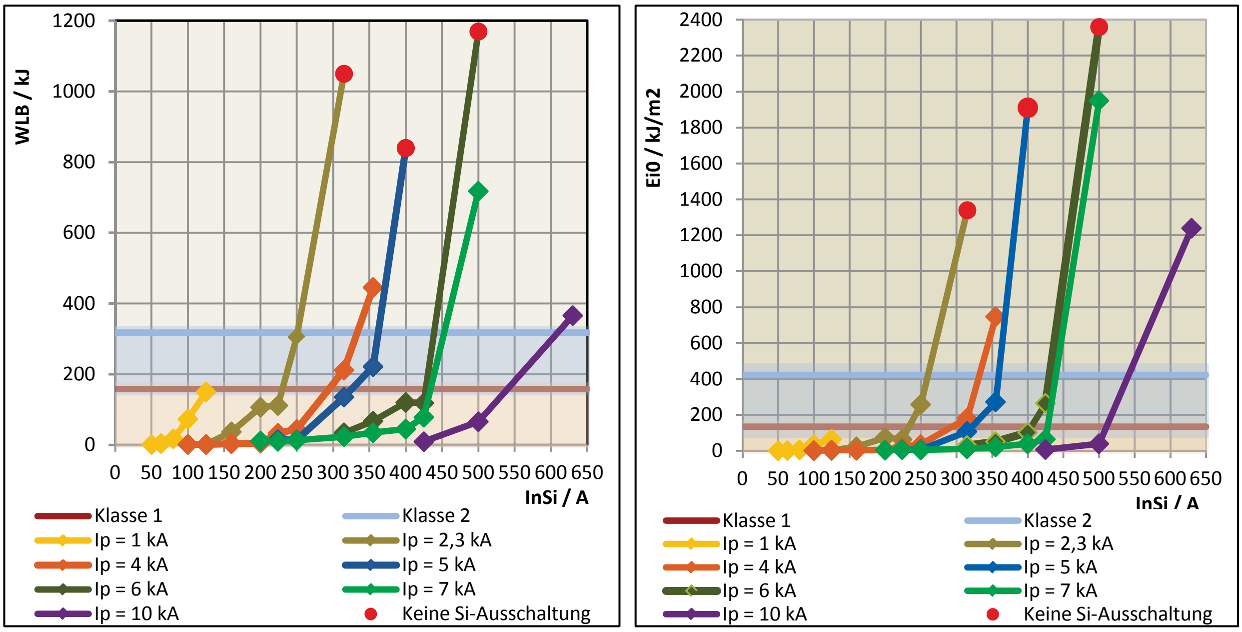


Fig.2: Arc energy W_{LB} (left) and incident energy E_{i0} (right) versus fuse rated current I_{nSi} of NH gG fuses, parameter: bolted short-circuit current I_P, limits of PPE class 1 (brown) and class 2 (blue) for standard exposure conditions

Fig. 2 shows the energy parameters obtained from the measurements for tests with full-range fuses for line protection NH gG. The PPE class 1 and class 2 protection levels are indicated in the diagrams. The crossing points of the approximation functions found for various fuse ratings in series of different prospective test currents (bolted short-circuit currents) provide the fuse rating up to which PPE provides personal protection for a certain short-circuit current level. Vice-versa, considering a diagram where the correlation between the energy parameters and the test current for each fuse rating is approximated, the limits of the short-circuit current up to which PPE protects in combination with a certain fuse rating can be derived.

Similar analyses were carried out for transformer fuses NH gTr and ultrafast work-protecting fuses.

3-phase arc tests with fuses

The electrode arrangement in the box used before was supplemented by a third electrode and supplied by a 3-phase test circuit with a fuse link in each line (see [6]). The electrode gaps are d = 30 mm. Test set-up and parameters are similar to those of the 2-phase tests in order to have comparable conditions. First arc tests with fix-adjusted arc durations (without fuses) have shown that different types of arc formation are likely in 3-phase systems. The arc power and arc energy resulting are also dependent on the electrode orientation. In case of configurations with opposing electrodes the ratio of the arc power (related to the 2-phase configuration) is about 2. In coplanar arrangements the ratio can be higher. In average, the arcs become longer since their columns are stronger enlarged particularly at the ends of electrodes. For higher currents there is an additional effect due to the material burn-up at the electrodes, it can increase the effective arc gaps and cause a higher ratio, too. The arc power in 3-phase systems may furthermore have very different values because the number of arcs involved in the fault can be different and change during the fault. There may be intermediate intervals of 2-phase arcs due to the extinction of an arc. In case of arcs migrating to the end of a coplanar electrode system there can be significant increases of the arc length, and a self-extinction of one or all arcs under circumstances. The arc energy is furthermore influenced by the arc duration. The direct exposure incident energy is moreover dependent on the material(s) of the electrodes. Different electrode materials and material combinations were used in the tests. The incident energy values measured can become very different, the highest levels appear if more than 2 electrodes are of aluminum.

In the tests for determining whether the PPE protection levels are kept or exceeded an electrode material combination aluminum – steel – copper was used. Tests were carried out in an arrangement of opposing electrodes (triangular configurations). That means that testing was based on average 3-phase conditions, no worst case scenarios were included.

The 3-phase arcing tests show that a simultaneous or nearly simultaneous cut-off of all three fuses with extinction of all arcs at the same time is an exception. In most cases one of the fuses cuts-off firstly, then the second and third fuse switch-off after a certain interval. The total arc duration as well as the arc power becomes influenced. The three fuse links in the three lines of the systems do not cut-off simultaneously or, as mentioned before, one of the fault arcs self-extinguishes (finally or intermediately), during 3-phase arcing faults intervals are likely to appear where the fault is only a

2-phase one. Within such 2-phase intervals mostly the arc and line currents are smaller than those in the 3-phase ones. For bolted faults the 2-phase short-circuit current is the 0.8667-fold of the 3-phase one. As the consequence the arc power is lower for 2-phase arcing. On the other hand the lower line current causes a longer fuse operation time. The total arc energy depends on both, the arc power and the arc duration, but with inverse tendencies. Three-phase arcing with 2-phase arc intervals needs not a priori lead to smaller arc energy compared to a continuous 3-phase fault. Theoretically longer arc duration could also cause higher total arc energy. However, in the tests conducted there has not been such case.
It should be mentioned that analyses of 3-phase arcing are to be continued in order to further verify the principle results found.

Practical guidelines for users

The results obtained from the laboratory measurements were prepared in a form that can easily be handled by a user when the selection of PPE and fuses is to be done or coordinated, respectively. These user guidelines extract the data needed in an abstract way, with concentrating to a few basic parameters which may easily to be overviewed and handled by users. These tools are directed to use the prospective bolted short-circuit current level (subtransient symmetrical short circuit current I''_k without arc influence) as input parameter since being available as the result of the conventional short-circuit calculation. As mentioned above, the actual fault currents of an arcing fault have lower levels, and may not well or proper be estimated or determined by users.

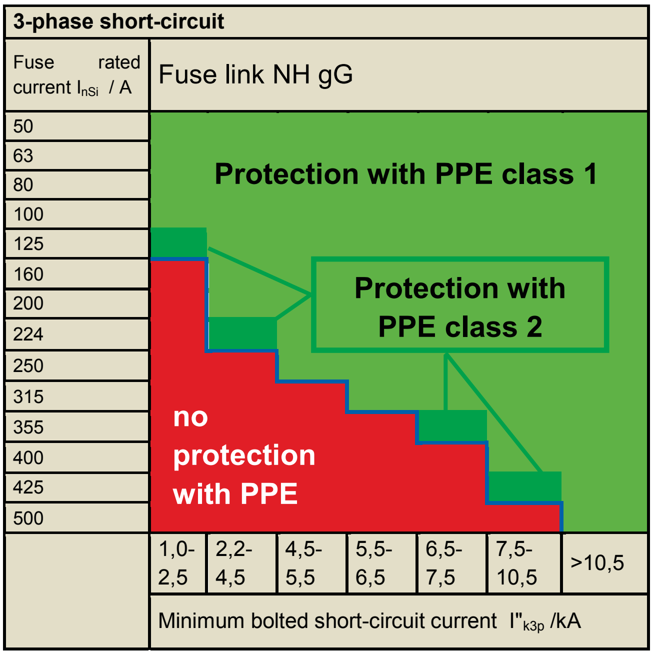
The user guidelines were prepared for 400 V 3-phase systems and standard exposure conditions (see above, Par. 3). There are 3 various forms differing in the degree of simplification, accuracy and manual handling: minimum over-current factor, selection matrix and normalized characteristic.

Minimum over-current factor: The over-current factor is the ratio of short-circuit current to fuse rating current. The maximum permissible fuse rating current $I_{nSi\ max}$ may very roughly be determined by using the minimum over-current factor in Tab. 1 and the prospective short-circuit current (for 2-phase short-circuit or 3-phase one) according to $I_{nSi\ max} = \frac{I''_k}{k_{Ü\ min}}$. The fuse rating current may not exceed this level when personal protection shall be provided by the PPE protection class accordingly selected.

Tab.1: Minimum over current factor $k_{Ü\ min}$

<table>
<tr><td>NH fuse link</td><td>PPE class</td><td colspan="2">Minimum over-current factor $k_{Ü\ min}$</td></tr>
<tr><td></td><td></td><td>2-phase short-circuit</td><td>3-phase short circuit</td></tr>
<tr><td rowspan="2">gG</td><td>1</td><td colspan="2">20</td></tr>
<tr><td>2</td><td>18</td><td>19</td></tr>
<tr><td rowspan="2">gTr</td><td>1</td><td colspan="2">28</td></tr>
<tr><td>2</td><td colspan="2">25</td></tr>
<tr><td rowspan="2">Working protection</td><td>1</td><td rowspan="2">6</td><td rowspan="2">8</td></tr>
<tr><td>2</td></tr>
</table>

Selection matrix: Matrixes correlating fuse rating currents and short-circuit current ranges for checking or selecting NH fuses were developed. From a matrix the minimum short-circuit current (lowest level of the permissible prospective current) can be read, required to provide personal protection with a certain fuse when using PPE of a selected class (see Fig. 3 and 4). For better handling separate matrixes for each type of NH fuses operation characteristic were generated for 2-phase short-circuits and 3-phase ones. The range of permissible conditions is colored green, in the red ranges protection is not given.



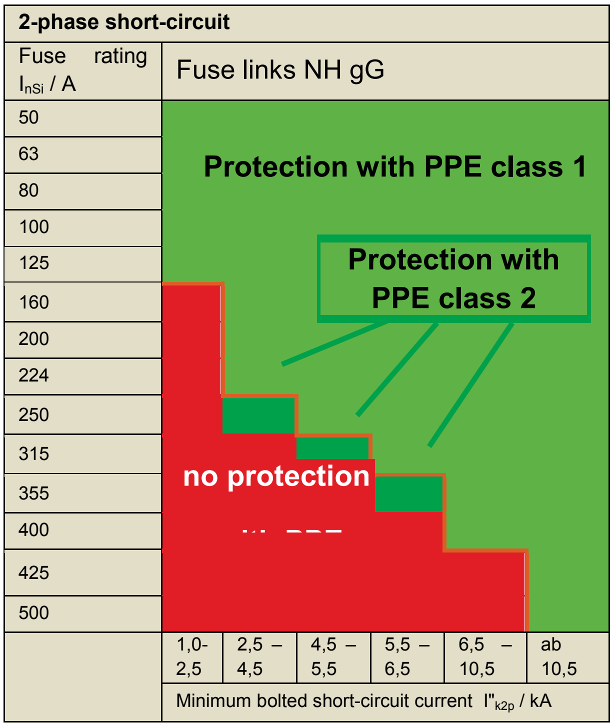


Fig. 3: Selection matrix for line protection fuses NH gG for 3-phase short-circuits (left) and 2-phase short-circuits (right)

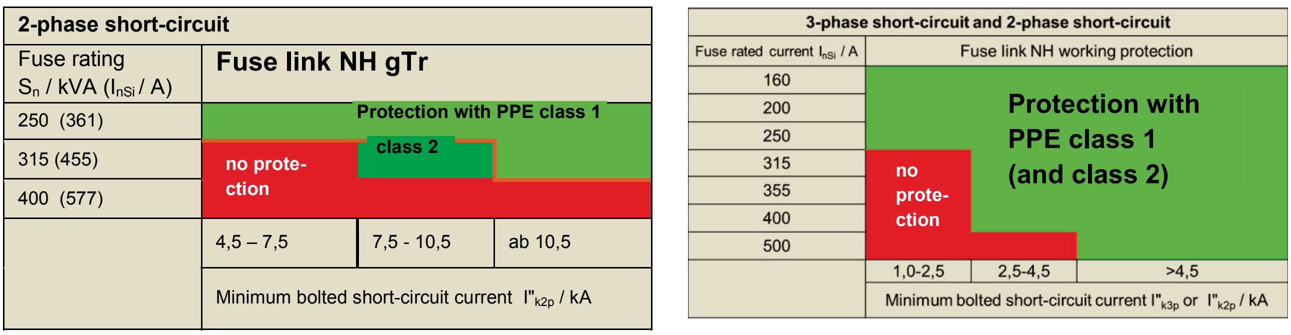


Fig. 4: Selection matrix for transformer fuses NH gTr (left) and NH working-protection fuses (right)

For 3-phase short-circuits, protection cannot be provided with NH gTr fuses of ratings > 250 kVA (neither with PPE class 1 nor class 2). With fuse ratings of 250 kVA or below protection is only achieved by PPE class 2 and when the short-circuit current is 7 kA or higher.

Generally, independently upon the fuse rating, personal protection (prevention of 2nd degree skin burns) may be assumed given under standard exposure conditions when short-circuit currents are below 1 kA in 400 V systems.

Normalized characteristic: Normalized characteristics were concluded in form of time-current dia-grams. The functions resulting are characterized by the equation $t_{k\ zul} = \frac{KL}{I_k^{"}}$ correlating the maximum permissible arc duration/fuse operation time and the prospective (bolted) short-circuit current. The diagrams do not show physical dependencies because the current causing the melting and cut-off of the fuse element is not identical with the bolted current in case of arcing in a LV system. The "artificial" functions were found as the upper limiting curves of actual measurement points transformed into the diagram conditions. The curve factor KL is shown for the different conditions in Tab. 2.

Tab. 2: Curve factor KL (in As)

PPE protection class	2-phase short-circuit	3-phase short-circuit
1	1000	500
2	2000	1000

On this base the maximum permissible fuse operation time based on the bolted short-circuit current can be determined. It has to be noted that the actual fuse cut-off time to be expected has to be found from the fuse manufacturer's operation time-current characteristic with using the attenuated arcing fault current.

More detailed information is submitted in [5] containing complete user tools, too.

Summary

Cutting-off of 2-phase and 3-phase arcing faults in 400 V systems by means of LV fuse links has been analyzed in laboratory arc test series, with measuring the remaining arc energy and thermal incident energy converted in the fault arcs and limited by the fuse operation. The conditions were determined under which personal protection may be submitted by using of PPE class 1 and class 2 according to IEC 61482-1-2. LV fuses are efficient means to achieve personal safety. The results were also summarized in form of user guidelines supplementing risk assessment and allowing reasoned coordination of fuse and PPE application. These simplified but safe rules need only to know the bolted short-circuit current and the operational current of the fuse of the feeder of the working place equipment, and relieve selection of the proper PPE and /or fuse. The use of an ultrafast working-protection fuse as technical personal protection measure is put on a reliable base. Personal protection is achievable in a very large number of working places in LV systems.

Acknowledgement
The author would like thanking NH/HH recycling e.V. (Club for promoting environment-equitable recycling of used NH/HH fuses), Germany, for supporting this work, and gratefully acknowledges this essential contribution.

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Conference: 10th International Conference on Electric Fuses and their Applications

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Frankfurt am Main, Germany
September, 2015