Fuse selection for providing personal and equipment protection against arc flash hazards in LV DC systems

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***Abstract*—Results of systematic theoretical analyses and lab measurements regarding the use of fuses for protecting personnel and equipment against arc flash in LV DC systems are presented and discussed. Aim of the work was the development and verification of a generalized method for the coordinated selection of high-power LV fuses and personal protective equipment (PPE) against the thermal hazards of high-power electric fault arcs. This new method includes two main aspects: the calculation of power and energy of DC fault arcs based on the system parameters and the determination of the fuse operating time out of fuse time-current characteristics, with taking into account the DC circuit time-constant and the current attenuation due to the fault arc. The procedure elaborated was verified by measurements in a DC test circuit with different types of NH fuses. As the result of the work, generalized fuse user information in form of a calculation tool are provided. The method shall also be introduced in user guidelines for selecting PPE.**

***Keywords*--Arc flash protection, DC power systems, electric NH fuses, low-voltage, personal protective equipment.**

I. Introduction

Arc flash occurring with short-circuit in electric power equipment is of high risk for the equipment itself and the persons working at such installations as well. The growing number and power ratings of DC systems in the low-voltage range (LV) of electric power supply increase the practical relevance and need of appropriate protection concepts. In case of faults in a large number of DC applications (control systems, DC micro grids, battery and storage systems, electro mobility etc.) and DC supply systems with inverters (traction supply, drives, decentralized power supply, wind energy converters, photovoltaic systems etc.) stable electric high-power arcs may occur which do not only cause damage and fire risk in the power equipment but also are of potential risk for personal injury due to the arc energies converted. Voltages and currents are in a range where stabile high-power arcs may exist.

High-current fault arcs (arc flash with short-circuits in the kA range) represent generally also big hazard for persons working near to live parts or executing live work in power equipment. While working, there is the risk of direct arc exposure. In analogy to AC systems the highest risk results from thermal arc hazards. Stabile arcs may particularly cause skin burns, and eye harms and injuries. Appropriate protection measures are needed.

Arc thermal hazard and protection needs are generally connected with the energy conversion in the arc, the factor time is playing an important role. Electric protection devices have to be used to limit the arc duration and arc energy. In addition, the application of Personal Protection Equipment (PPE) is required regarding personal protection against arc flash with short-circuit in DC power systems when there is the general risk of direct arc exposure. When selecting, the coordination of electric protection devices and PPE is needed for providing personal protection in DC systems, too. Fuses may render an important contribution to achieve personal protection.

Knowledge and information on DC fault arcs from literature is relatively limited. DC systems are often still not or not directly in the scope of standards and guidelines for users. Up to now there was also the open question in terms of transferring or assigning experiences and knowledge of AC arcs and PPE selection to the DC range. Research work was started to find evidenced information on low-voltage high-current DC arc parameters and, based on this, about the appropriate and coordinated selection of high-power fuses and PPE in LV DC systems. Laboratory measurements on high-current arcs were important part of this research. In the following, selected practically relevant results of the work shall be considered.

II. Focus High-Current Arc Flash and Arcing Fault Protection Aims

It has generally to be distinguished between series fault arcs with limited power conversion and high-power arc flash with high risk for personal injury and equipment damage. High-power fault arcs occur especially with short-circuit (in parallel to loads). With short-circuit in switchgear assemblies, in distribution systems as well as at equipment connection terminals the occurring arcs are connected with over-currents (often kA range) and high power and energy release. High-current and high-power arc flash causes equipment damage and outage, and hazards to persons when working at the equipment (live working or work in the vicinity to live parts). In contrast, series fault arc occurring with conductor interruption, contact and insulation faults in installation systems are accompanied by fault currents in the range of operational currents (often A range). The power conversion being limited, there is mainly an increased fire risk. Although strict distinction is not possible in each case, the focus is directed to high-power arc flash in the following.

It is known from 3-phase AC systems that arc hazards, risk assessment, the protection aims and the selection of protection means have to be based on the arc energy W_{arc} to be expected at the fault place. The expectation values of arc energy may not exceed the permissible arc energy W_{perm} for achieving a planned arc protection aim:

$$W_{arc} \leq W_{perm}. \qquad (1)$$

There may be different protection aims and strategies. For power equipment in closed construction (e.g. not-opened metal-clad switchgear) arc energy thresholds for conditioned personal protection and equipment functional protection are known from 3-phase AC systems [1].

In connection with the personal protection by means of PPE in case of direct arc exposure (open or opened equipment) the energy threshold is connected with the arc energy test levels W_{test} of the internationally standardized box test according to IEC 61482-1-2 [2] which is normally used as base for PPE certification in Europe. The PPE protection levels as permissible arc energy result from the box test levels. If the arc exposure scenario is similar to the box test standard conditions (working distance a = 300 mm and small-scale equipment volume with a heat transmission factor of $k_T = 1$) the test levels are also the protection ones [3]. For deviating conditions (a > 300 mm, open arc or large-scale volume with $k_T > 1$ [3]) the protection levels are determined by

$$W_{perm} = W_{test} \cdot k_T \cdot (a/300\ \text{mm})^2. \qquad (2)$$

Table 1 gives an overview on the different arc protection energy thresholds.

TABLE 1. ENERGY THRESHOLDS FOR DIFFERENT PROTECTION AIMS

Protection aim	**Threshold W_{perm}**		W_{test}
Personal protection	Equation (2)	PPE APC 1	168 kJ
		PPE APC 2	320 kJ
Conditioned personal protection	250 kJ		
Equipment functional protection	100 kJ		

First own tests on different PPE (materials of protective clothing, face shields) show equipment does not behave differently in terms of the thermal resistivity and the heat transfer when tested in an AC test circuit or a DC one. Consequently, the arc energy thresholds may be used also for characterizing the protection aim and PPE intended to apply in a DC system.

III. Laboratory Measurements

Laboratory measurements in DC test circuits were aimed at achieving knowledge on the DC arc and risk parameters, and finding information on arc power and energy levels to be expected in real DC systems. Furthermore, the behaviour of NH fuse links with special focus on the remaining fault arc energy was analysed.

Measurements took place in test circuits supplied by different types of DC source: high-voltage Li-Ion car battery (with a varied number of modules; no-load source voltages 48…400 V), induction generator (300 kW, 800 V, 8 kA), and a rectifier (6-pulse converter bridge). Fig. 1 shows the principle scheme of the test circuit. A special battery source aspect is the increase of the inner battery resistance and no-load voltage with the number of modules (series connection). In case of the induction generator the source voltage is controlled by the separate-excited system and a fly-wheel. The converter bridge is a stable linear source (no-load voltage and inner resistance are constant). Different test parameters were set. The no-load voltage was varied between 100 and 1000 V, the prospective short-circuit current between 1 and 20 kA. The circuit time constant $\tau = L/R$ was in the range $\tau = 3…15$ ms.

Electrode arrangements of opposing electrodes of different materials with and without box were taken into consideration. A small-scale box surrounding the electrodes with the same dimensions and construction as in the PPE Box Test [1] was used. The electrode gap d was varied. Flat and conical electrode forms as well as different electrode materials were used [4].

Test were carried out with fuses interrupting the circuit, and - for general information and comparison - also without NH fuse links with a fixed switch-off time of the test circuit breaker. Different types of fuse links were used: line protection fuses NH gG (400 V and 500 V), ultra-fast work-protective fuses NH gR (400 V and 500 V) and fuses for photo-voltaic systems NH gPV (750 V). Fuses with different rated currents were applied. The types NH gG and gR are no special fuses for DC applications but also intended for use in AC systems.

On the base of the recorded voltage and current data the fault arc power and energy were determined. The direct exposure incident energy was measured by means of two calorimeters placed in a plate analogously to the Box Test set-up. The exposure distance was a = 300 mm. A typical oscillograph of a test with fuse link NH gPV is also shown in Fig. 1.

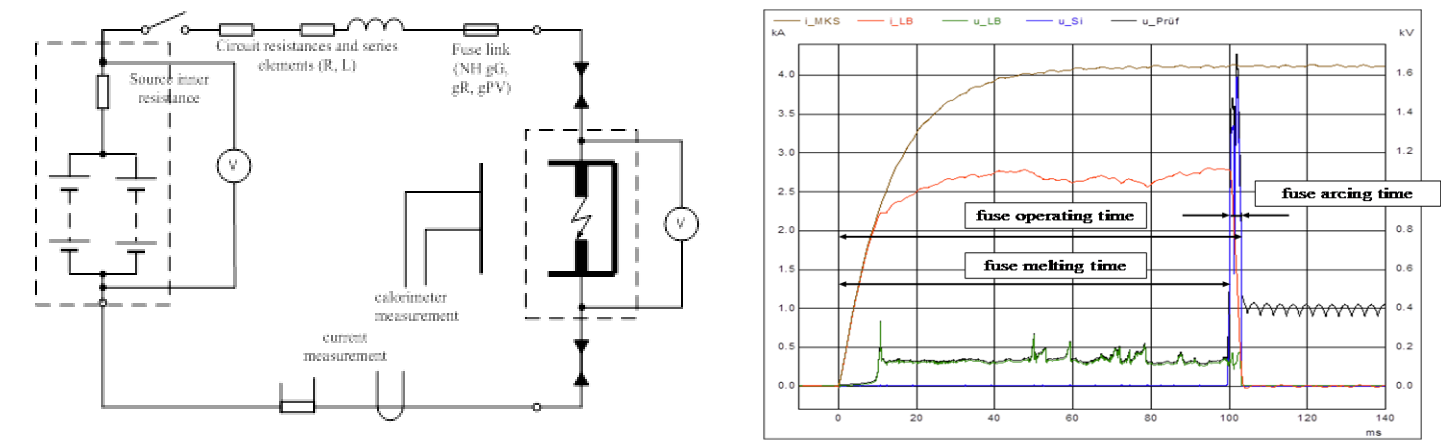

Figure 1. Left side: Principle scheme of the DC test circuit (Circuit with battery source); right side: Typical oscillograph of an arc fault test with fuse link (bolted short-circuit current - brown, fault arc current - red, fault arc voltage - green, fuse voltage - blue, system voltage - black)

IV. FUSE BEHAVIOR

As already described in chapter III, different types of fuse links (gG, gR, gPV) were used in the laboratory tests in the DC circuit with metallic short-circuit and also with fault arc. In general, the whole operating time of a fuse link is divided into melting time and arcing time (switching arc inside the fuse). For each test the fuse behavior/performance was recorded. Figure 2 shows the melting time measured in relation to the ratio of short-circuit current and current rating (I_k/I_{nSi}) for the three different fuse types in case of tests with fault arc as well as a comparison to the melting times of gG fuses in case of metallic short-circuit. In general, it is found that with a decreasing ratio of metallic short-circuit current to fuse current rating, the melting times are increasing and the fuse arcing times are decreasing.

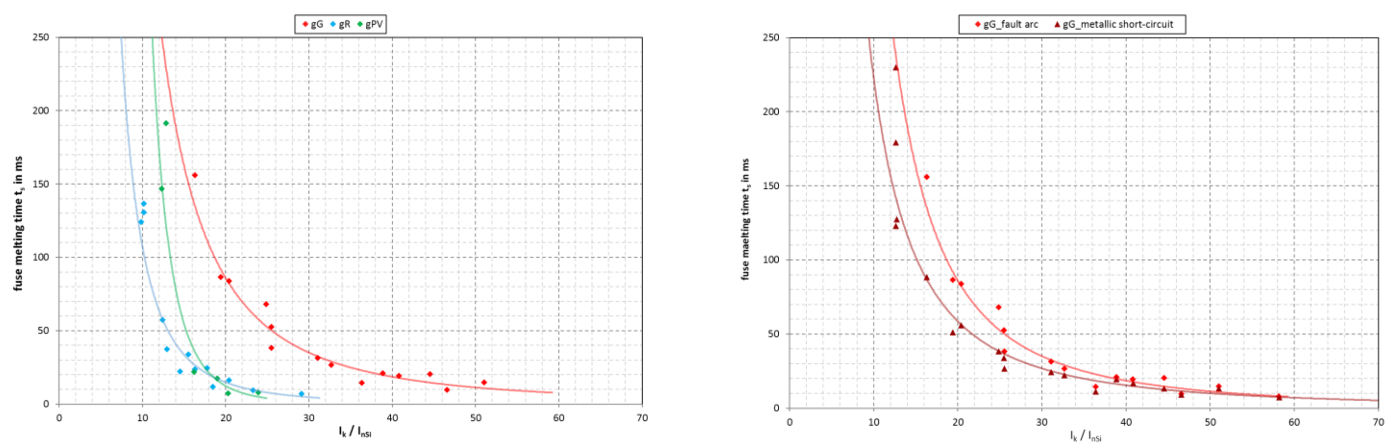

Figure 2. Left side: measurement results of the melting time for different fuse types (gG, gR, gPV) in case of tests with fault arc; right side: measurement results of the melting time for gG fuses in case of tests with fault arc or metallic short-circuit

Melting times are longer in case of arc faults compared to metallic short circuit because of the current attenuation due to the arc resistance. Figure 2 shows that the NH gG fuse links (red line) have the highest melting times when comparing the three types. Especially for values of the ratio between bolted fault current and current rating of the fuse less than 30 gG fuse links cause high melting times and therefore high operating times too, which means a higher arc duration and arc energy as well as an increased arc flash hazard. A similar behavior is shown by gR (blue line) and gPV (green line) fuses. When using gPV fuses, higher melting times result for small current ratios in the range of 10-15.

Furthermore, the arcing time (switching arc inside the fuse) is much higher and shows a greater dispersion when using gG fuse links compared to both other types in a DC circuit. Nevertheless, the measurement results indicate in most cases that the arcing time has a very small part of the whole operating time of the fuses (see figure 1). In this phase the arc current is lowered to zero and the electric arc energy (fault arc) is almost negligible.

The measurement results and the performance of the fuses show that the use of fuses for providing personal and equipment protection in LV DC systems is an efficient means. For an appropriate fuse selection an accurate determination of the expected value of the arc current is required in a first step.

V. CALCULATION OF ARC CURRENT (CURRENT ATTENUATION) AND ARC POWER

Measurements have shown that equations known from literature for calculating the electric arc parameters and the heat flux ones [5-7] are not sufficient. Average deviations between measurement results and calculation ones are 27,5 % and maximum deviations 57,5 % for the electric parameters. In terms of the heat parameters (incident energy) the deviations are still much higher (118 % in average, 243 % maximum. The measurement results were used for fitting empirical equations for this reason, and also for adapting the physically based description of the arc current-voltage characteristic according to Stokes/Oppenlander [5]. The arc characteristic with adapted coefficient values is

$$U_{arc} = (34 + 0{,}532 \cdot d) \cdot I_{arc}^{0{,}12} \qquad (3)$$

and represents a relatively well approach of the measurement result. The average deviation between measurement results and calculation ones is about 10,1 %, the maximum deviation is 45 %. Based on this approach the arc voltage, arc current, and finally arc power and energy may be calculated in an iterative procedure. Therefore, the general linearized relation of an electrical DC short-circuit with fault arc is used with

$$I_{arc} = U_N / (U_{arc}/I_{arc} + U_N/I_k), \qquad (4)$$

where U_N is the rated system voltage and I_k is the prospective short-circuit current. By inserting the arc characteristic (3) in equation (4) the recursion formula for the iterative calculation of the arc current

$$I_{arc\,(i+1)} = U_N / [(34 + 0{,}532 \cdot d)/I_{arc\,(i)}^{0{,}88} + U_N/I_k)] \qquad (5)$$

is determined for the i+1-th step of the procedure. After the selection of an initial value of the arc current (e.g. $I_{arc\,(0)} = 0{,}5 \cdot I_k$) and a convergence criterion (e.g. 10^{-5} A) the expected value of the arc current can be calculated with (5) for the respective parameters of the DC short-circuit and electrode gap d at the fault location. By using (3), the associated value of the arc voltage is determined and the expected value of the arc power P_{arc} is estimated by multiplication of arc current and arc voltage.

In LVDC systems the arc current is less than the prospective short-circuit current because of the current attenuation, which is described by

$$k_B = I_{arc} / I_k. \qquad (6)$$

This current relation represents an important aspect for determining the operating time of the respective protection device (e.g. a fuse) in the electrical circuit as well as to calculate the electrical arc energy W_{arc}.

VI. CALCULATION OF THE ACTUAL FUSE OPERATING TIME BY CONSIDERING THE TIME CONSTANT

The fuse manufacturers provide a time-current characteristic or diagram based on the melting integral of the fuse melting wire. The diagrams show the virtual melting time of fuses of different rated currents as functions of the current flowing through the fuse. A constant DC current which follows a step function /step-wise rise is assumed with these diagrams. Actually, in case of short-circuit (bolted fault or arc flash) there is a limited rate of current rise which is determined by the time constant of the electric circuit τ = L/R (inductive and resistive circuit elements). The difference of the melting integral for both the step function and the limited rate of the current rise based on an example is shown in Figure 3.

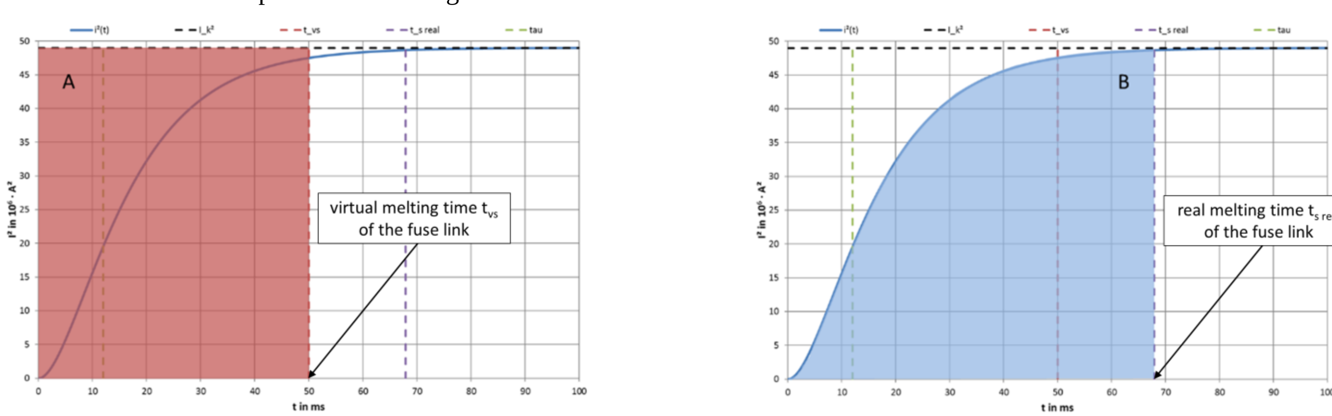

Figure 3. Melting integral (i²t) of a fuse (example) for: A) step function of the squared current (τ = 0); B) limited rate of squared current rise as a consequence of the time constant of the electric circuit (τ > 0)

The red (A) and the blue area (B) represent the melting integral (i²t) of an exemplary fuse wire. Both areas are the same size, but because of the different current rises the resulting melting times are also different. In order to determine the real melting time of the fuse considering the time constant of the DC circuit, the two areas are set equal with

$$I_k^2 \cdot t_{vs} = \int_0^{t_{s\,real}} I_k^2 \cdot \left(1 - \exp\left(-t/\tau\right)\right)^2 \,. \qquad (7)$$

By solving equation (7) the real melting time of the fuse link is calculated by

$$t_{s\,real\,(i+1)} = 0{,}5\tau \cdot \exp(-2t_{s\,real\,(i)}/\tau) - 2\tau \cdot \exp(-t_{s\,real\,(i)}/\tau) + t_{vs} + 1{,}5\tau \qquad (8)$$

with an iterative procedure. Analogous to the calculation of the arc current in chapter V an initial value for $t_{s\,real}$ and a convergence criterion must be defined. For the former it is useful to choose the virtual melting time, which can be determined by using the time-current diagram of the respective fuse. The real melting time is due to the time constant always higher than the virtual melting time of the fuse. This has a significant influence on the arc duration and thus also on the electrical energy of the fault arc.

VII. Algorithm for Selecting Fuse Links for Arc Flash Protection in LVDC Systems

In a general procedure for fuse selection both the current attenuation due to the fault arc and the time constant of the short-circuit path have to be taken into account. The consideration of these influences has been described in the chapters before. Fig. 4 shows the flow chart of the total algorithm allowing a fuse link to be selected in combination with the arc flash protection aim (e.g. PPE application). The procedure is based on input parameters which are usually known for the DC systems: rated system voltage, prospective short-circuit current, electrode gap, time constant. In the first step the actual fault current (fault arc current) is determined by using these parameters of the fault location in the DC system under consideration. Compared with the bolted short-circuit current, this fault arc current is reduced due to the attenuation effect of the non-linear fault arc resistance. Often this current is significantly smaller than the bolted one. The arc current is calculated iteratively. Starting with an appropriate start value the iteration is carried out until a selected convergence criterion is reached. As the result, the expectation values of the arc current and arc voltage are found, and - by multiplication - the arc power.

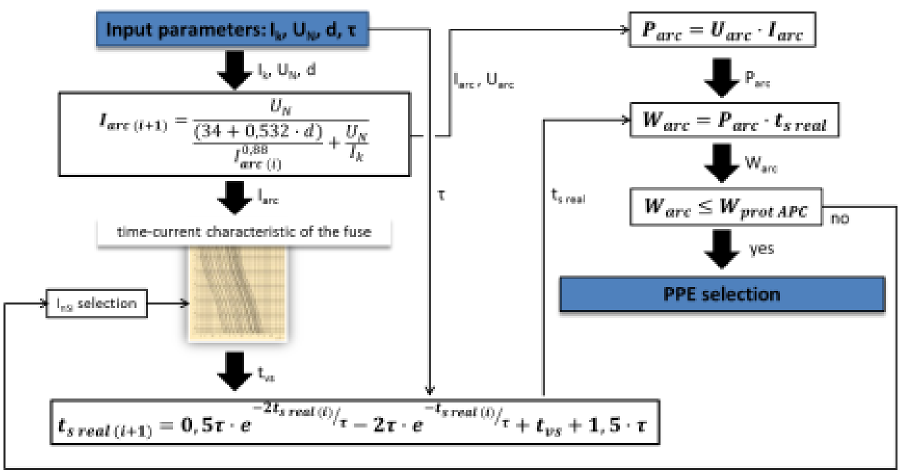

Figure 4. Flow chart of the total algorithm for fuse and PPE selection

With the expectation value of the actual fault arc current the virtual melting time t_{vs} is determined from the time-current diagram for the characteristic of that rated current I_{nSi} of the fuse selected or used in the branch feeding the arcing fault location in the case under study. This virtual melting time is directly taken from the according specific time-current characteristic. In the next step the actual operating time of the fuse is iteratively calculated with taking into account the DC fault circuit time constant $\tau = L/R$ according to the procedure pointed out in paragraph VI. Using an appropriate start value the iteration process is carried out until a preset convergence criterion is reached.

The resulting expectation value of the actual fuse operating time is the increased real arc fault duration with taking into account the fault arc current attenuation effect and the time constant influence on the transient current time function.

In the next step the electric fault arc energy is calculated with the arc power and the actual fuse operating time

$$W_{arc} = P_{arc} \cdot t_{s\,real}. \qquad (9)$$

This expected fault arc energy will be converted in DC system with the specific electric system parameters when the arc flash is switched-off by the selected fuse (manufacturer, operating type, rated fuse current). The arc energy expectation value has to be compared with the threshold values related to a certain protection aim. In case of PPE selection, the protection levels $W_{prot\,APC}$ have to be considered which result from the box test levels $W_{test\,APC}$ (see Par. II). If there is

$$W_{arc} \leq W_{prot\,APC\,1} \qquad (10)$$

PPE of arc protection class APC 1 is sufficient. Otherwise, PPE of APC 2 has to be used for work activities in the according DC system. If the expected arc energy level exceeds also the protection level of APC 2 PPE

$$W_{arc} > W_{prot\ APC\ 2} \qquad (11)$$

the selected PPE is not sufficient under these system conditions, and other measures have to be applied. One option is to use another fuse (different fuse rated current or fuse type) which has a shorter virtual operating time. Selecting a faster fuse operating type and/or smaller current rating, the procedure has to repeated (determination of fuse actual operating time and arc energy) until the expected arc energy will not exceed the energy protection level, and the protection aim is finally reached.

As mentioned above, not only the PPE protection levels may be taken into consideration in this way but also the other protection energy levels (see Tab. 1). Generally, it has to be proved that the expected arc energy is smaller than the protection energy threshold value.

The application of the procedure was described for the scenario of selecting PPE for a given DC system (including fuse). The procedure may also be applied in the opposite way with starting with the protection aim (energy threshold) and looking for the fuse which is required to reach it (e.g. maximum fuse current rating). First the arc power to be expected has to be determined again iteratively and based on the DC system electric and geometrical parameters (as described above). With the energy threshold value of the protection aim under study the maximum allowed arc duration is calculated

$$t_{arc\ max} = W_{perm}/P_{arc} \qquad (12)$$

This is the maximum actual fuse operating time $t_{s\ real}$ allowed. By using the equation

$$t_{vs} = 2\tau \cdot \exp(-t_{s\ real}/\tau) - 0,5\tau \cdot \exp(-2t_{s\ real}/\tau) + t_{s\ real} - 1,5\tau \qquad (13)$$

the maximum virtual operating time is calculated. This value gives a limit in form of a straight horizontal line in the time-current diagram of the fuse type. Together with the expectation value of the fault arc current it results in a diagram section characterizing allowed conditions regarding fuse ratings by which the considered protection aim may be reached.

VIII. Summary

The coordination of applying high-power LV fuses with the selection of personal protective equipment (PPE) is an efficient mean for protecting personnel and equipment against arc flash also in LV DC systems. Theoretical analyses and measurements were made for finding and verifying calculation procedures for the determination of arc energy to be expected in case of an arc flash. On this base a procedure was developed with taking into account the current attenuation effect of the fault arc as well as the increase of the fuse actual melting resulting from the time constant of the electric circuit. The fuse melting time has to be determined with the actual fault arc current. Consideration of the time constant leads to a better precision of the arc energy values.

The procedure elaborated is a general tool for users, and is thought to become part of user guides.

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References

[1] Schau, H. ; Halinka, A.; Winkler, W.: Elektrische Schutzeinrichtungen in Industrienetzen und –anlagen (Electrical protective devices in industrial power systems and equipment), in German, München/Heidelberg: Hüthig & Pflaum Verlag, 2008, ISBN 978-3-8101-0255-3

[2] IEC 61482-1-2: Live working – Protective clothing against the thermal hazards of an electric arc – Part 1 Test methods, Part 1-2 Determination of the arc protection class of textile material and clothing by using a directed and constrained arc (box test), 2nd edition 10-2014 (published also as EN 61482-1-2 and VDE 0682-306-1-2)

[3] DGUV-I 203-078 (formerly BGI/GUV-I 5188 E): Thermal hazards from electric fault arc - Guide to the selection of personal protective equipment for electrical work, Information, Publisher: German Social Accident Insurance e.V. (DGUV), October 2012

[4] Schau, H.: Risk parameters of DC fault arcs – research work on DC arcs in LV systems. ICOLIM 2017 Strasbourg /France, Proceedings IEEE public. 978-1-5090-5132-8/17

[5] Stokes, A. D.; Oppenlander, W. T.: Electric arcs in open air. Journal of Physics D: Applied Physics, 1991, pp. 26-35

[6] Ammerman, R. F., Gammon, T., Sen, P.K., Nelson, J.P.: DC arc models and incident energy calculations. IEEE Transactions on Industry Applications, Vol. 46, No. 5, Sept/Oct 2010, pp 1810-1819

[7] Wilkins, R.; Allison, M.; Lang, M.: Improved Method for Arc Flash Hazard Analysis,. Proc. IEEE Industrial and Commercial Power Systems Technical Conference, May 2004