Reduction of the arc fault energy during live working thanks to the interaction of fuses and a modular protection system

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Introduction

There is an increased arc fault risk during live working. Persons working on opened systems are directly exposed to the effects of an arc fault. Such an arc fault can cause high risks due to the thermal energy, the pressure wave, the high radiation intensity, the sound, the toxic gases and the hot particles. Personal protective equipment (PPE) can limit the thermal effect below a certain limit of the arc energy so that persons are protected from second degree burns. However, PPE only provides limited protection against the other effects of an arc fault. This paper deals with technical measures which are capable of reducing the effects of an arc fault and the residual risks during live working in the low-voltage range.

Effects of arc faults

Under the normal conditions present in low-voltage systems, arc faults with stable burning can only form from currents of approx. 1000 A. Below this threshold the arcs are extinguished on their own with little damage [1]. An arc fault burning freely in a low-voltage system migrates at a speed of up to 100 m/s in the opposite direction to the incoming supply. The effect of the arc primarily depends on the direct and indirect exposure of the environment to its temperature and radiation. The temperature of the freely burning arc is normally between 10 and 20 TK. The melting and vaporisation of material is therefore not restricted to the bus bars but also affects all isolating parts, as a result of direct contact or radiation. In this process, particularly polymers may release toxic and even reactive gases. The amount of these secondary decomposition products significantly exceeds the consumption of the metallic electrodes particularly in case of long-duration arcs. Due to the base points of the arc on the electrodes, not only vaporised metal, but also melted metal with droplet sizes of several millimetres is removed and spread over several meters due to the pressure of the arc. Measurements have shown that an arc with a current of about 3 kA, a comparably low arc voltage of < 120 V and a duration of about 900 ms already leads to a consumption of about 20 g aluminium (about 7000 mm³) or 28 g copper (about 3000 mm³). In case of higher currents or longer durations, the quantity of melted and particularly vaporised metal significantly increases. However, the electromagnetic radiation in the IR-UV (infrared-ultraviolet) range may directly cause irreversible skin and eye damage. The pressure build-up reaches its maximum after approx.

10-15 milliseconds, i.e. after the peak current value has been exceeded. The sound intensity behaves in a similar way. This can reach values of over 170 dB at a distance of 1 m [1], [2]. To reduce or prevent damage to systems and persons, active and passive arc fault protection measures can be implemented. The active measures are aimed here at preventing the causes leading to the arc fault and can include increasing the distances, selecting and applying insulating material as well as monitoring and detection measures that cause the disconnection of the system before the arc occurs [1], [2]. These measures, however, cannot completely prevent arc formation particularly during live working. Therefore, passive and reactive arc fault protection measures, which are effective within a few milliseconds if a fault occurs, have already been implemented in some low-voltage systems. To ensure rapid arc fault protection, an additional short-circuiter is often tripped with a delay of a few milliseconds, in addition to the immediate actuation of switchgear by the detection unit. In this way, the arc fault is quenched considerably earlier than the disconnection provided by the overcurrent protective devices. The requirements for such devices are described in the IEC 60364-4-42 [3] standard. Light detection or a combination of light and current detection has proven itself in LV systems to detect the arc fault. Line and/or point sensors are frequently used for light detection. The primary protection goal of these permanently installed devices is to protect systems and persons in closed systems. In order to achieve these protection goals, the energy of the arc must be limited to values < 100 kWs (system protection) and values < 250 kWs (personal protection) [1].

Mobile short-circuiter for live working

The installation of arc fault protection systems with fixed short-circuiters is normally restricted to systems requiring a high level of availability combined with high short-circuit ratings. Only a small proportion of systems are therefore provided with an arc fault protection system with short-circuiter for maintenance work that has to be carried out under live conditions. However, live working is widely used and is particularly performed in systems which are protected by current-limiting fuses on the low-voltage or medium-voltage side. Figure 1 shows such an arrangement with an incoming supply of 630 kVA.

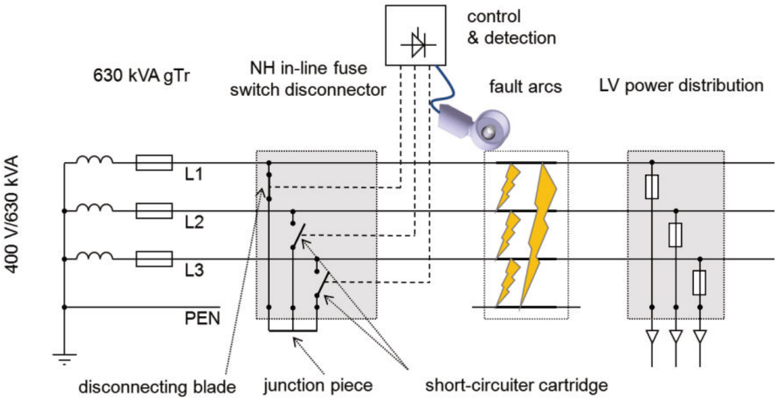

Figure 1:
Low-voltage supply with short-circuiter

Persons may be directly exposed to arc faults when carrying out live working, for example at low-voltage distribution boards. Therefore, it is mandatory to wear PPE during live working. This equipment is available in two protection classes (class 1 basic protection, class 2 increased arc protection) and is suitable for reducing the thermal effect of arc faults at a specified working distance of normally 30 cm, so that a person does not suffer from second degree burns.
IEC 61482-1-2 [5] stipulates that protection against arc fault energies up to 158 kJ is ensured with PPE class 1 and up to 318 kJ with class 2. The German DGUV information 203-077 [6] provides assistance in assessing the thermal risks resulting from arc faults and selecting PPE. The additional use of a mobile short-circuiter to optimise personal protection during live working is useful in order to achieve a drastic reduction of the thermal effect and also the other effects of the arc fault in particular. This kind of additional protective device has some different requirements in part compared to a fixed installation. Live working requires mobile use of the protective system as much as possible [7]. Live working is largely carried out in systems with a lower power rating compared to industrial systems. In the public utility sector, 80 % of the systems have prospective short-circuit currents in the 10 kA range [8]. Fuses are generally used as overcurrent protective devices in these systems. The systems are also seldom provided with directly accessible current measuring devices. During live working, the arc fault is frequently caused at the equipment of the switchboard and not directly at the bus bars. The installation of current measuring devices and optical line sensors locally would thus cause a considerable hazard. The arc fault protection system therefore operates with purely optical arc fault detection using point sensors. The purely optical detection places some demanding requirements on the sensors and the evaluation of the optical radiation with regard to the tripping reliability and the prevention of nuisance tripping.

Detection system

During live working, however, it cannot be assumed that the system is closed, but rather that external light or even additional intensive lighting is present. The withdrawing of fuses under load and normal operational switching may also be necessary during live working. This, however, will produce a visible switching arc amongst other things. To prevent nuisance tripping, a detection unit of the arc fault protection system evaluates a threshold value of the illuminance for a fixed duration (> 1 ms), as well as the relative change in illuminance at a specific gradient (9000 lx / ms). Tests in a realistic environment showed that this evaluation was sufficiently insensitive to disturbance from external light, normal flash lights and indirect sunlight. The switching arcs of modern switchgear as well as the withdrawing of fuses under load at currents even above > 1 kA likewise are not detected as arc faults [7]. The evaluation unit can nevertheless detect arc faults with short lengths (> 1 cm) at a current of approx.1 kA even within 10-20 ms.

The detection time required drops to approx. 3 ms with higher currents. Due to the additional light evaluation, the time here is longer compared to permanently installed equipment. However, this is sufficient due to the lower system power present during live working and the current-limiting NH fuses, which are passive when they are not tripped. During live working, the arc fault may be covered by sections of the system or by the person carrying out the work.

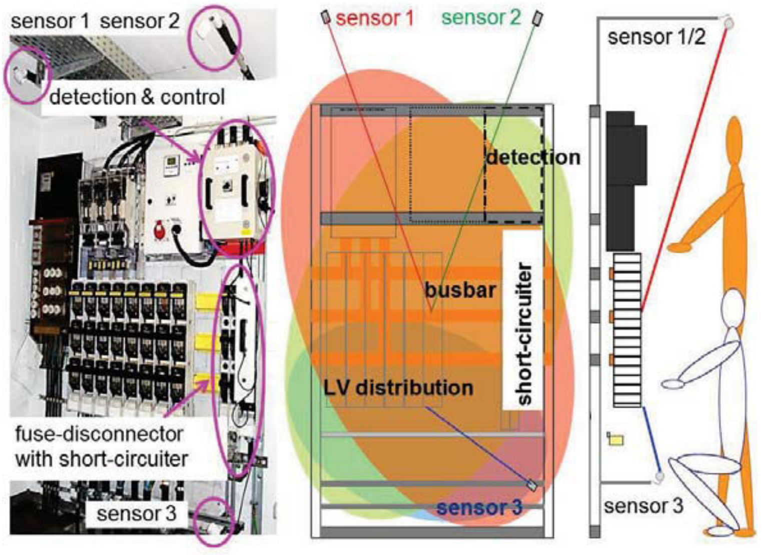

Figure 2:
Low-voltage system with protection area of the mobile arc fault protection system

Several point sensors can be provided here in order to ensure high detection reliability despite this. Figure 2 shows an example of this kind of system. In this case, the system can be monitored fully and redundantly with three sensors (overlapping colour areas) with high detection reliability with arc faults of only 1 kA. This has been demonstrated in extensive tests using standing and crouching dummies. Fewer sensors are sufficient when the light intensity of the arc is higher or the working areas are defined. Sensors are provided with shields and reflectors to improve the reliability of detection and protection from disturbance. This enables reliable detection from several meters away as well as optimum alignment in different systems through the use of a cover for external radiation and defined detection cones.

Short-circuiter

The short-circuiter preferably consists of only two units with an NH design, which are each arranged between the two phases. Figure 3 shows the basic principle for the short-circuiter cartridges. The main contacts are kept apart with an isolated melting tube. Therefore, the two units are isolated in the normal state and can be changed to the short-circuit state by activation. Current flows through the melting tube for a short period of time and overloads it. As a result, the metallic main contacts are closed under spring pressure. As shown in Figures 1 & 3, a special NH in-line fuse switch disconnector, which is also lockable, can be installed or provided in the system for higher short-circuit currents and higher incoming supplies of up to 630 kVA. This in-line fuse switch disconnector can be used as spare outgoing feeder in normal operation. A so-called junction piece is provided in the outgoing feeder area for “short-circuiter“operation. Two short-circuiters with an NH design as well as a disconnecting blade are inserted in this in-line fuse switch disconnector. The two short-circuiters are activated via the trigger connection by means of a control unit. After that, a three-pole bolted short-circuit is generated in the system by the junction piece, the two short-circuiters and the disconnecting blade, thus reliably quenching the arc fault.

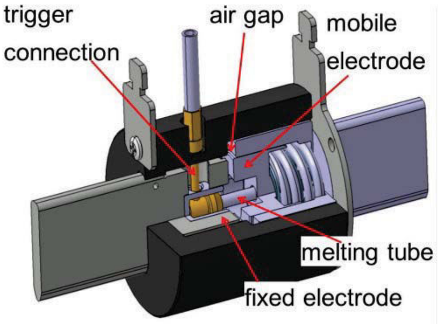

Figure 3:
Functional principle of the short-circuiter cartridge

In addition to the components with an NH design, other main components of the system, the control unit with the integrated detection device and the optical point sensors can be arranged in a mobile box which is only used for live working. The lockable in-line fuse switch disconnector and the sensor supports may already be provided in new systems, in old systems they can be retrofitted during live working. If an in-line fuse switch disconnector is pre-mounted, all further preparatory work (work in the vicinity of live parts) can be performed without PPE until the short-circuiter system is operational. During installation, the sensors are inserted into the relevant supports. The defined insertion of the sensors into the pre-mounted support and the forced installation for the relevant system ensures reliable detection. The short-circuiters and the disconnecting blade are inserted into the in-line fuse switch disconnector which is then locked. After that, the two short-circuiters and the disconnecting blade are connected to the control unit via control lines. An automatic functional check is performed after commissioning the control unit. Now the required maintenance work can be performed under live conditions using PPE. The design, installation and functional principle of such an arrangement are described in detail in [9]. When locked, the in-line fuse switch disconnector can carry short-circuit currents of 25 kA (peak currents of 53 kA) for 1 s. In addition to the short-circuit current carrying capability, the in-line fuse switch disconnector also limits the continuous current carrying capability of the system to 630 A.

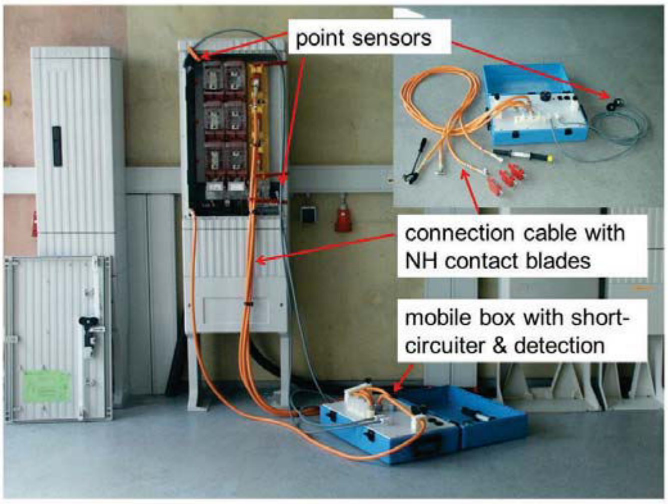

Figure 4:
Low-voltage system with mobile arc fault protection system

The short-circuiters can also be arranged in the mobile box with the detection unit and the control unit for prospective short-circuit currents of approx. 10 kA. This box has at least three connection cables with which it can be connected to the system for example via NH contact blades. A special in-line fuse switch disconnector or locking is not required in this performance range. Any existing in-line fuse switch disconnector is suitable for installation. A junction piece does not have to be used in the outgoing feeder area of the in-line fuse switch disconnector. The box itself can also be provided with a battery for a stand-alone power supply and can house its connection cables and optical sensors. Figure 4 shows this type of arrangement installed in an LV system with two point sensors.

Benefits and operation in LV systems with electrical fuses

The main benefits of NH fuses are their high current limitation and their low tripping times for high prospective currents. Under these conditions, the passive fuses are often capable of sufficiently protecting systems and persons in case of a fault. Recent tests [10] demonstrated the protective effect of NH fuses in case of arc faults. These tests show that NH gG fuses sufficiently protect persons wearing class 2 PPE against the thermal effects of the arc in case of high overcurrents which are at least 19 higher than the nominal current. However, they also show that fuses with small nominal currents of e.g. NH 160 A gG do not provide sufficient protection in case of low overcurrents and thus long arc fault durations. The actual arc fault current which forms the basis for selecting the personal PPE can be considerably reduced by means of the impedance of the arc fault compared to the known prospective short-circuit current at the work location. If the prospective short-circuit current is only limited to 50 % [6], a fuse can drastically reduce the disconnection time. The actual current limitation, however, heavily depends on the fault location, the system parameters, the type of fault and the fault development. Both considerably lower and higher limitations of about 30-70 % are known [4], [11]. In case of long times, it is particularly difficult to transfer the characteristic curve of a fuse to the behaviour in case of an arc fault since long zero current intervals occur in the zero crossing area or the current flow of the arc fault is interrupted in some half waves. These stochastic effects even considerably increase the actual pre-arcing time of the fuse compared to the characteristic curve which assumes continuous current flow. The current/time diagram in Figure 5 shows the characteristic curves of two NH fuses, arc-fault-protected PPE (class 1 and 2) and the mobile short-circuiter. The actual average current values (arc fault current values) must be used to assess the protective effect of the PPE and therefore the figure additionally shows the characteristic curves of the fuses which result from the current limitation of the prospective short-circuit current by the arc fault to 70 % ($k_B = 0.7$). In case of higher limitations to 50 % or even 30 %, the disconnection time of the fuse is further increased. Assuming prospective currents and a current reduction to only 70 %, the NH 315 A gG fuse, for example, provides sufficient thermal protection in case of a two-phase fault at only about 6 kA (158 kJ) in combination with a class 1 PPE. In case of a three-phase fault, a class 2 PPE (318 kJ) is required for this current value. If a NH 630 kVA gTr fuse is used, the currents must be higher than approx. 11 kA. In this case, class 1 or class 2 PPE does not provide sufficient protection against the thermal risks of an arc fault in case of lower arc fault currents. The characteristic curve of the mobile short-circuiter is considerably below the characteristic curves of the PPE. The NH fuses intersect the characteristic curve at extremely high currents. If the actual current values exceed these maximum currents, the detection and response time of the short-circuiter does not have advantages over a NH fuse. In case of lower currents or higher current limitation by the arc faults, the arc fault duration is considerably limited compared to the mere protection by a fuse. The limit values of conventional PPE are significantly undercut in this case.

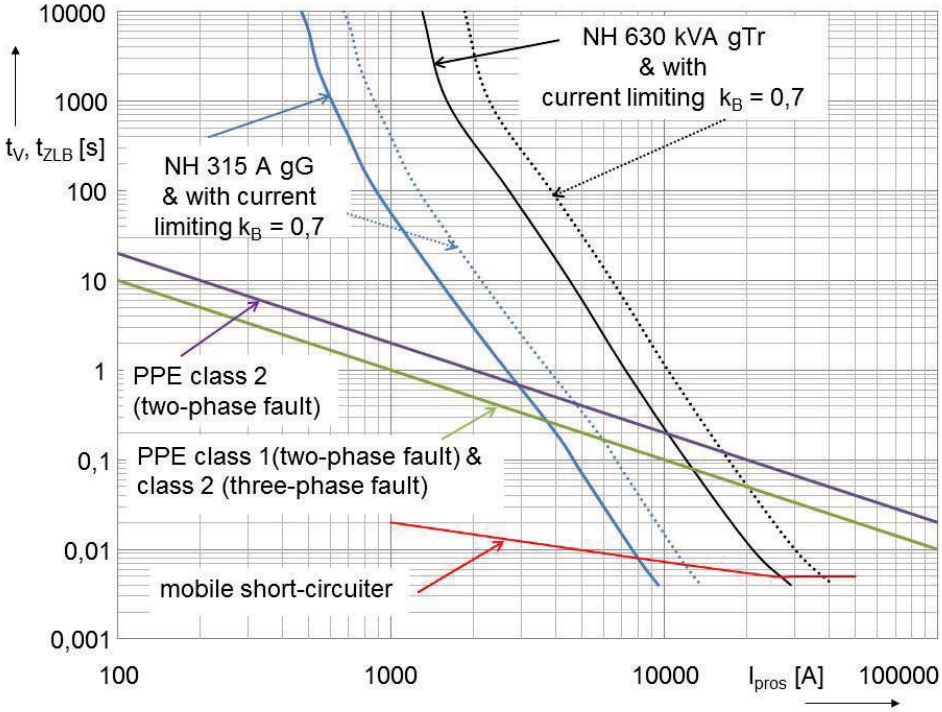

Figure 5:
Time/current characteristic curve shows the interaction of NH fuses and a mobile short-circuiter under consideration of the protective effect of PPE in case of an arc fault [10]

I_{pros} – RMS Prospective Current, t_V – Virtual Pre-arcing Time, t_{ZLB} – Permissible Arc Fault Duration

In combination with current-limiting fuses, the required detection and short-circuit time of 5 ms for currents > 8 kA is sufficient for systems. The benefits of using an additional technical solution (short-circuiter) for live working [6] become particular evident in case of low actual arc fault currents. In case of these low currents, protection is provided by the reliable detection of the arc fault detection device up to about 1 kA, namely in the lower persistence limit of arc faults in low-voltage systems [1]. The slightly longer detection time in this range of about 20 ms does not have any negative effects on personal protection. The benefit of the additional short-circuiter can be seen based on the example of a low-voltage system with a performance of 630 kVA. Such widely used systems typically have prospective short-circuit currents between 16 and 23 kA and are provided with NH 630 kVA-gTr fuses. The disconnection time for this prospective short-circuit current is some ms. If the current is limited to 50 % [6], the disconnection time of the fuse increases to more than 100 ms. In case of an arc fault, the load limit of a class 2 PPE can thus be reached or exceeded. At 10 kA and a high arc voltage of e.g. 200 V, the short-circuiter would reduce the arc energy resulting from a three-phase fault to less than 30 kJ. This value is not exceeded between 1 kA and 25 kA. Since the PPE is only loaded with a small portion of this energy [6] this value is considerably below its load limits. An additional short-circuiter allows to limit both the arc and current flow duration in the system to a few milliseconds since the fuse is loaded with almost the prospective short-circuit current after the system has been activated. After the short-circuiter has tripped, the unreduced prospective short-circuit current acts on the fuse and the disconnection time of the fuse is equal to the actual characteristic curve. In case of extremely high currents, the dynamic load on the low-voltage system does not increase due to the bolted short-circuit if the short-circuiter is combined with NH fuses. The considerable time limitation of the arc fault drastically reduces the thermal effect of the arc fault, the radiation effect, the pressure wave, the sound, the metal vapours, the metal particles, the toxic gases and the pyrolysis, thus considerably improving the protection of the system and particularly persons carrying out live working.

Summary

Short-circuiters can considerably reduce the effect of arc faults in LV systems. This improved protection can be achieved particularly with permanently installed devices for systems with very high short-circuit ratings. In this way, the effort required for the restoration of service and the downtimes can be kept to a minimum. Personnel protection is naturally also improved as well as system protection. A mobile system can be used to provide additional protection for low and medium power systems, which are normally not equipped with a permanently installed arc fault protection system. This is particularly useful for live working in combination with PPE [6] since persons may be directly exposed to arc faults. A sufficiently fast and reliable detection of arc faults can be achieved with little additional effort, even under special conditions of live working.

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