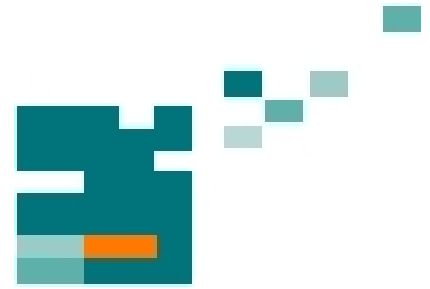# 54. IWK

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TECHNISCHE UNIVERSITÄT ILMENAU

PROVING OF THE TRIPPING SAFETY OF A NOVEL DEVICE FOR ARC FLASH PROTECTION

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ABSTRACT

Detecting and extinguishing electric arcs ultra-fast within some milliseconds, a novel mobile protection device also provides efficient personal protection against the thermal hazards of an electric fault arc in the short circuit current range of up to 15 kA in case of direct exposure due to opened L.V. installations during live working or working in the vicinity of live parts. The paper is reporting on laboratory measurements for proving the protection system tripping safety and immunity against malfunctions. Main focus is directed to the detection unit of the protection system. Based on an optimized design of the optical detectors unit the protection device is prepared for use in the practical work.

Index Terms – Electric power installations, low-voltage switchgear assemblies, arc flash protection, protection device, live working

1. INTRODUCTION

Fault arcs are of potential risk for the injury of persons working in or at electrical power installations, particularly when there is the danger of a direct exposure as in case of live working or working in the vicinity of live parts.

An effective personal protection is achieved if the arc duration was significantly limited. According protection devices must guarantee a fast detection and extinction of the arcs. A mobile construction enables the operational use of the device for a great variety of working activities in very different distribution boards of the L.V. systems.

An according protection system has been developed and designed for a short circuit current range typically for working activities on opened installations in LV systems. The contacting adaptors for the operational use of the protective devise have been tested for short-circuit currents of up to 10…15 kA, so the protection system may be applied in this range.

For the arc extinction a special short-circuit unit (short-circuiter) is used whose reliable and efficient function in the 3-phase systems of the different L.V. network types was proved by measurements in the high-power test lab. This has already been reported in

[1]. Besides of the fast current commutation and arc quenching, the reliable detection of the arcs was proved. The selected optical arc detection system was analyzed with respect to the detection safety and detection time delay on the one hand, and the immunity against optical disturbances and tripping malfunctions on the other hand. In the following selected results of these investigations are shown and discussed.

2. PROTECTION SYSTEM

One essential component of the protection system is the short circuiter unit, performed by 3 short-circuit contacts in star connection. The function and efficiency in extinguishing fault arcs in L.V. installations was investigated and proved in the test lab in 3-phase AC systems under the conditions of the different L.V. system types [1]. The test circuit of the power lab matches the conditions of a TN or TT system. The test transformer neutral is directly grounded, a 4-wire system is available in the test lab.

The conditions of a IT system may be simulated by introducing of an additional (large) impedance into the neutral, thus a decoupling of the transformer neutral potential is achieved from the fourth conductor that is resulting from this as PE one. Fig. 1 shows the principle electric test circuit.

The short-circuiter was tested together with contact adaptors and an optical detection system in the test lab. In systematic test measurements practically relevant and critical application cases were simulated. The transient record of an example is shown in Fig. 2. The protection system provides very fast arc extinction, so there are in general extreme short arcing times for all types of faults and system configurations. The remaining thermal hazards of electric fault arcs extinguished by the protection system are not dangerous. There are no essential thermal incident energies in a distance of 300 mm to the arc, skin burns of persons can be excluded without any doubt. In all tests the electric arc energy and the incident energy (relevant for skin burns) were significantly smaller than those levels characterizing the personal protection classes 1 and 2 of arc protective clothing.
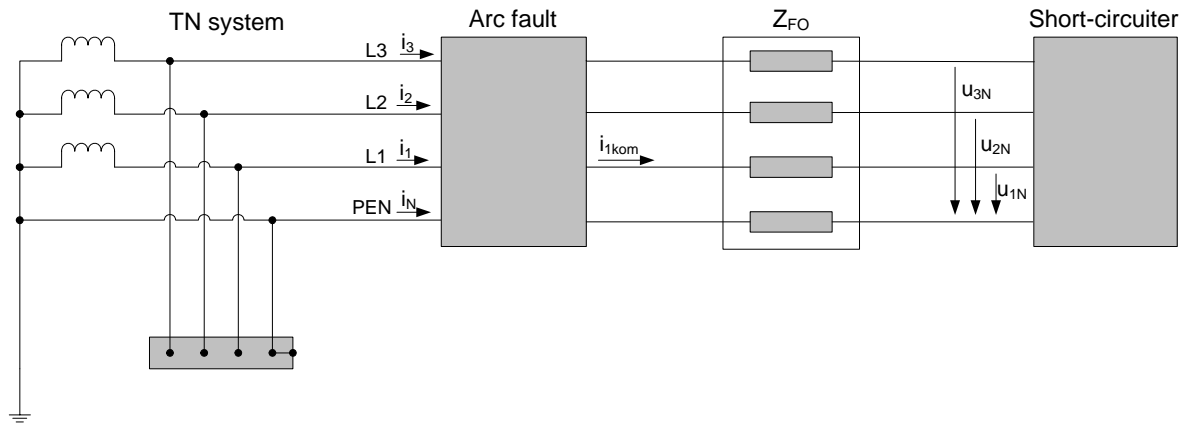
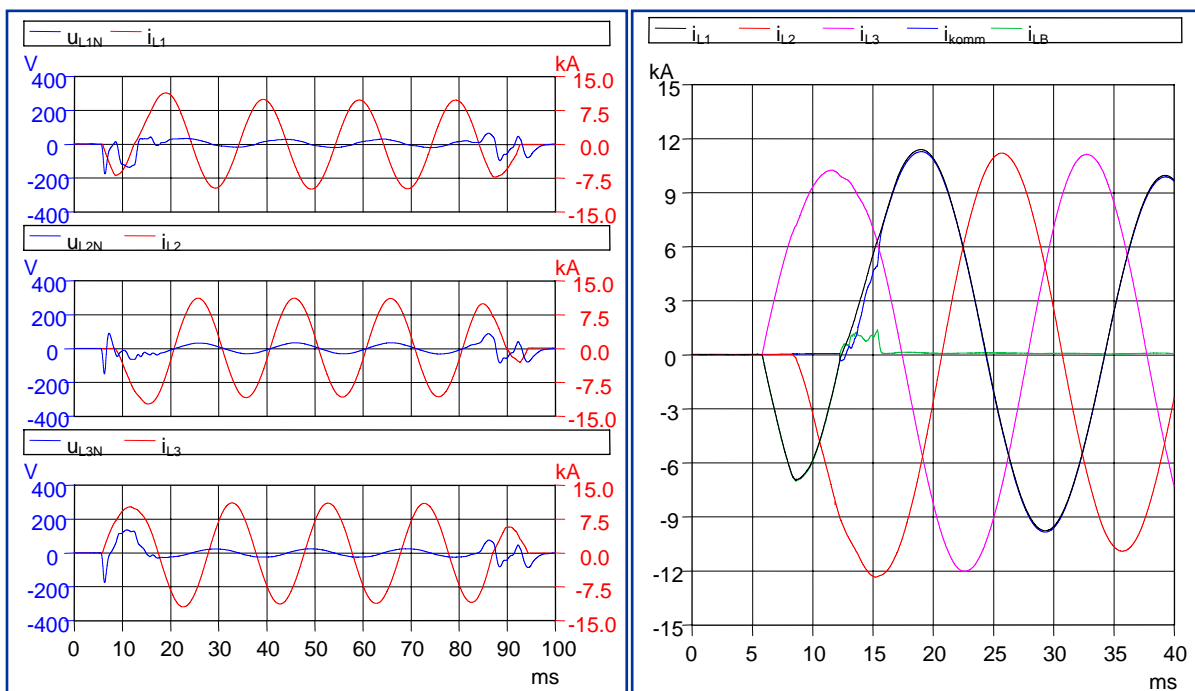*Figure 1: Test circuit and measurement parameters*

Figure 2: Transient record of the extinction of a 3-phase-to-ground short-circuit in a TN system (short-circuit current 7 kA) based on a real arc detection (active control)

In the example of Fig. 2 the tripping delay of the total system is $t_{trip} = t_{KS} + t_{Erf} = 7{,}1$ ms (complying with the arc duration). It consists of the short-circuiter commutation time for extinguishing the arc $t_{KS} = t_{komm} = 3{,}6$ ms and the detection delay $t_V = 3{,}5$ ms.

In the laboratory tests the total time between the firing of the arc and the generation of a control signal for the short-circuiter t_{VG} consists of the detection delay t_V and the time period t_D necessary for the melting of the fuse wire used for firing the arcs in the tests. Thus the detection delay is $t_V = t_{VG} - t_D$. Fig. 3 illustrates these conditions by an example (example selected for showing time definitions only: very long detection time due to low-power arc with large sensor distance, short-circuiter is.not activated).

The arc detection is based on a technical solution available as an accomplished product on the market. The detection system LBW 21 [2] used consists of optical sensors and an evaluation/control unit with voltage supply. This system is a fabricate and available as a complete one including an optional overcurrent detection (current input). In the mobile device the current detection is however not activated (current input is bridged), so it is used as a pure optical system detecting exclusively the light emission of an arc flash. The optical sensors are plastics globe ones (principle of the Ulbricht sphere) connected to the control unit via two light conductors (optical fibers). One conductor is the sensor fiber, the other one is used for monitoring the whole optical fiber system by conducting a modulated light signal to the sensor head.
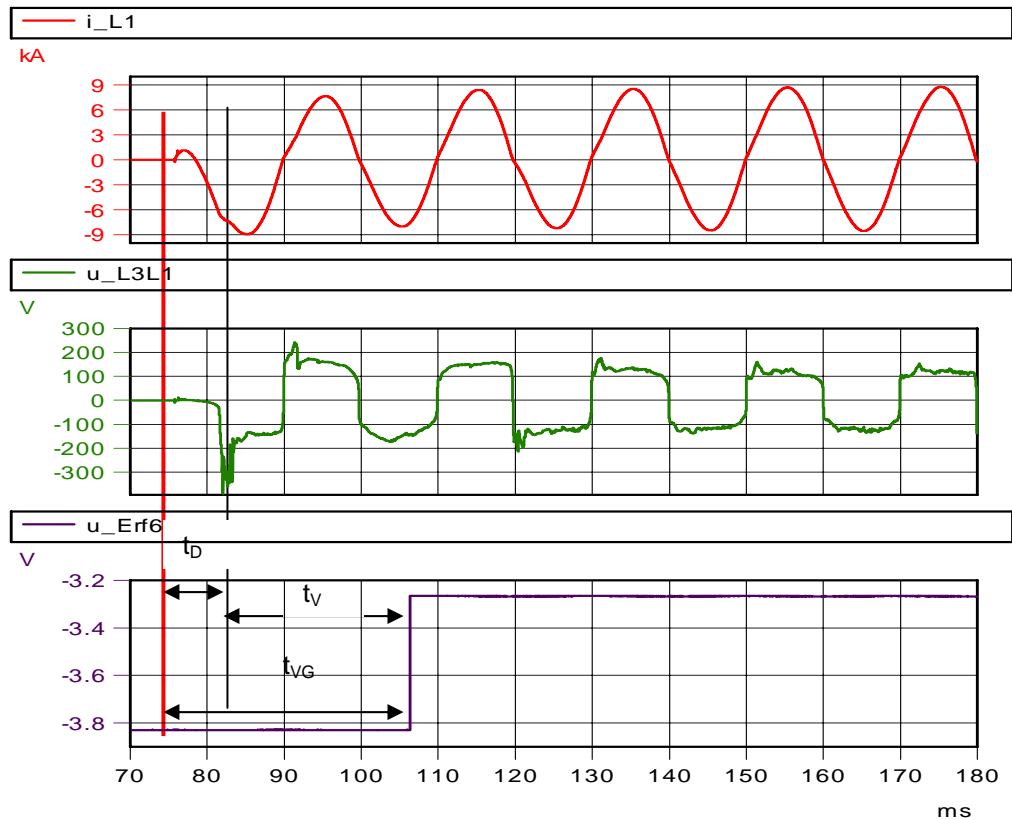
Figure 3: Records of the arc detection investigation parameters with arc current (above), arc voltage (mid) and detection voltage signal (below, with time parameters)

The optical system is particularly constructed for detecting light changes in order to reach a safe fault arc indication. Referring the detected optical signal three criteria are assessed to be matched:

1. Minimum signal altitude (determines the signal threshold)
2. Minimum signal ascent time (gradation threshold)
3. Minimum arc existence time (signal time period above the threshold).

The detection algorithm used determines the ascent of the signal coming from the sensor and sets a marker if the minimum ascent time and threshold are reached. The marker remains set as long as the received signal drops below the threshold. A counter is then decremented with constant time interval, the third criterion of an arc is matched when the value becomes zero. If the signal drops below the threshold before the counter lapse, counter and marker are reset. Light emissions of durations from 2…3 ms are detected by this.

As shown by the arc tests made the minimum detection time of the system is $t_V = 3…3.5$ ms. This is the time delay of the detection unit. There is a release (detection signal creation) if the constant luminance is higher than 120,000 lx. For sudden luminance changes the detection threshold is 9,000 lx.

Very extensive investigations were focussed to the reliable function of the optical sensor system and the safety against malfunction.

3. DETECTION SAFETY AND DETECTION DELAY

The optical sensor system behavior was tested in several series with

- different distances (distance sensor to arc a)
- positions (horizontal position h, vertical position v; direct exposure, sensor partial and total covering or shadowing)
- arc current levels (or prospective test current I_p respectively)
- electrode gaps d and materials (Cu, Al).

The detection delay was measured. The electric fault arcs were fired in a 2-phase vertical electrode configuration with a surrounding box (as used in testing PPE according to IEC or EN 61482-1-2). Fig. 4 shows the principle test set-up with the sensor positions investigated in the test series. The sensor position is related to the arc axis (horizontally) and the middle of the electrode gap (vertically) and is characterized by the distance a and the space angle h,v. Due to the geometrical symmetry these positions are distributed on the periphery of an one-eighth

sphere (there are analogous conditions for the 4 eighth-spheres), with the sensor distance as radius. Following the central sensor position is P = 0,0 (h = 0 and v = 0).
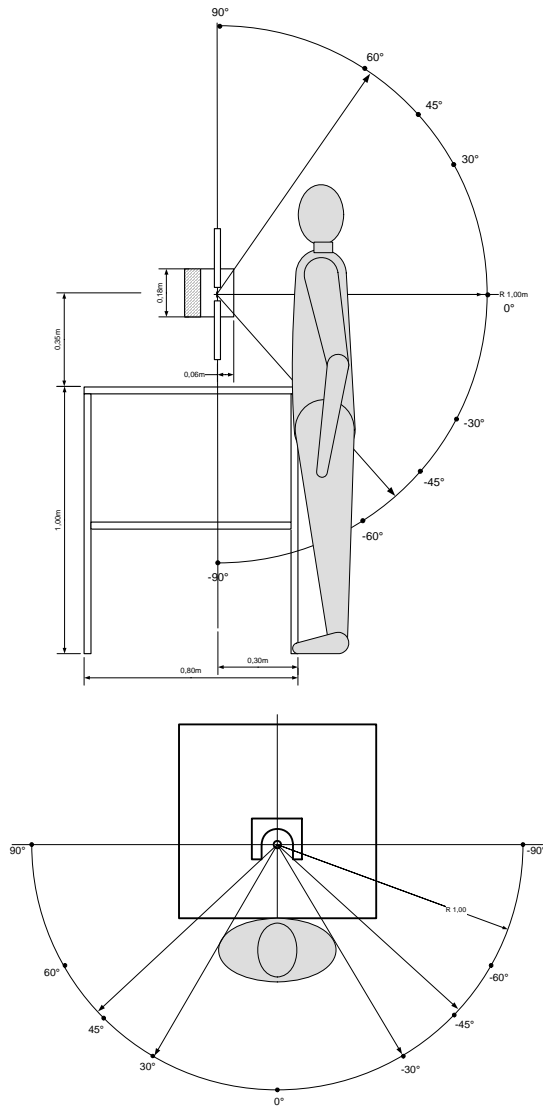

Figure 4: Test set-up with dummy and sensor positions (above: side view; below: top view)

Fig. 5 shows the detection time t_V with variation of the sensor distance a to the arc column (arc axis).

The level of the arc power and energy determining the intensity of the radiation and light emission depends on the short-circuit current and the electrode gap influence. The standard parameter adjusted in the test series were a prospective current of 4 kA and an electrode gap of 30 mm resulting in an arc power of about P_{LB} = 440 kW or arc energy of W_{LB} = 44 kJ (average values). From the experience it may be estimated that parameters do not fall below those levels very often in actual fault events in LV installations. The Tables 1 and 2 show the arc

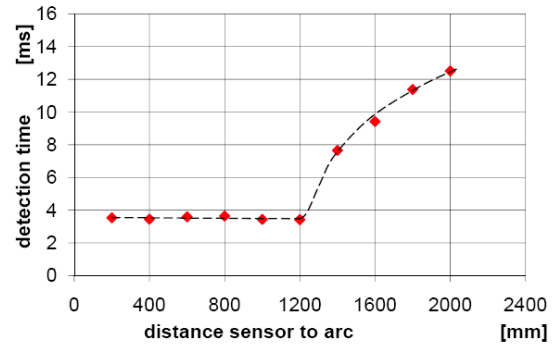parameters for electrode gaps of 10 mm and 30 mm with an arc duration of 100 ms.

Figure 5: Detection time in dependency on the sensor distance for standard parameters

Since the optical detection is most critically if there are very short electric arcs with very small short-circuit currents, also tests were made under existence borderline conditions (1 kA) and with smallest arc column formation (d = 10 mm) in order to find the detection limits.

Table 1: Parameters for arc duration 100ms and electrode gap 10mm

Short-circuit current (prospective)	1kA	4kA	7kA
Arc power P_{LB} [kW]	124	380	616
Arc energy W_{LB} [kWs]	8,6	38	59

Table 2: Parameters for arc duration 100ms and electrode gap 30mm

Short-circuit current (prospective)	1kA	4kA	7kA
Arc power P_{LB} [kW]	*	438	741
Arc energy W_{LB} [kWs]	*	44	70

* 1-kA tests with 30 mm electrode gap were not carried out

The Fig. 6 shows examples of the arc detection. The arc current, arc voltage as well as the electric output signal of the detection unit with 2 optical sensors in different positions are presented (the short-circuiter was not activated in these tests). In the first example (Fig. 6a) an electric arc at the existence borderline (see above) with extreme weak light emission was detected in a sensor distance of 2 m. The detection delay was $t_V = t_{VG} - t_D$ = 46,03 ms – 29,86 ms = 16,17 ms. The extremely long "wire period" results from firing an arc in a test circuit of very small short-circuit capacity (low-power arc). In the example of Fig. 6b there is an arc of I_P = 7 kA and d = 30 mm (sensor distance a = 2 m); here the detection delay $t_V = t_{VG} - t_D$ = 6,92 ms – 3,08 ms = 3,84 ms lies in the range of the minimum delay.
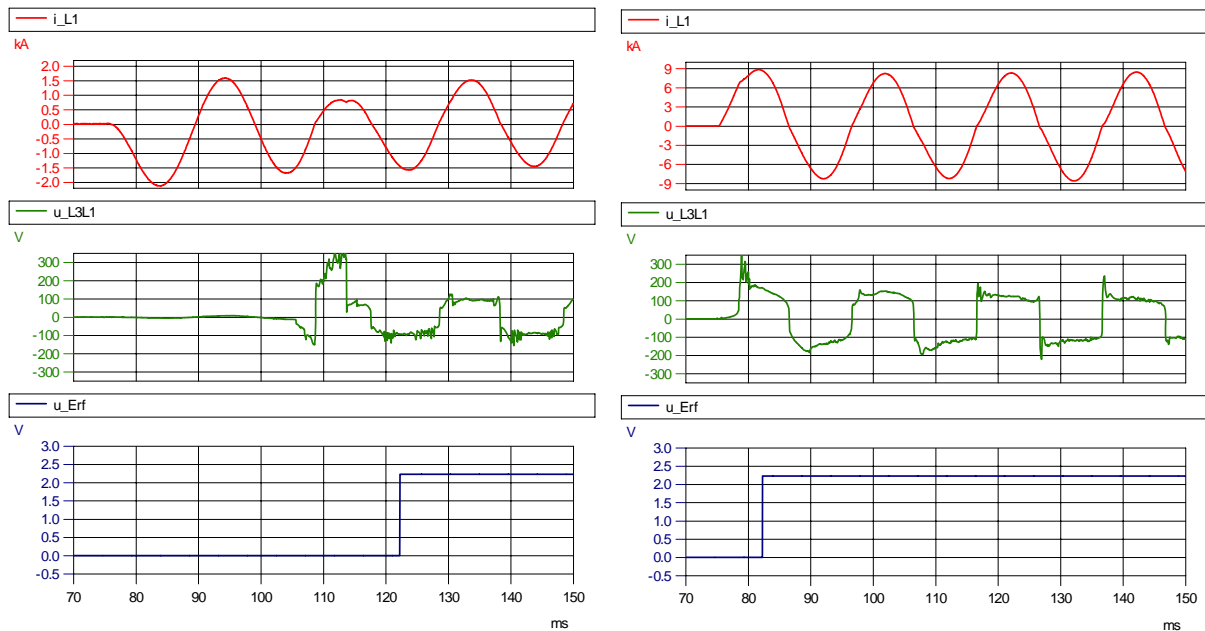
Figure 6: Time curves of the arc parameters and the detection delay for a) a low intensity arc at the existence border (left) and b) an arc of higher intensity (right)

In general for high arc intensities the reaction time (tripping delay) of the detection system is about 3.5 ms, with low light intensity the reaction time can increase to tens of milliseconds. That also appears in case of sensor shadowing or covering. From the tests can be concluded that a good tripping safety with acceptable detection time can be achieved by using two sensors. Sensor positions are suitable if the distance a to the detection zone was not larger than 2 m in principle; ideal is a < 1m.

The test series carried out with variations of the sensor positions give information on whether and with what influence on the detection time there is a detection for certain sensor distance ranges and for direct or only indirect irradiation. Practically, sensor shadowing or covering can result e.g. from the persons or parts of their bodies when working. Detailed test series were also made, for this reason, with a dummy (with jacket) placed in front of the arc with a distance of 300 mm to the arc axis (the arc box was centred to the breast bone of the dummy torso, see Fig. 4). Under standard parameter conditions there is an influence of the configuration and shadowing effects on the detection time t_V as summarized in Fig. 7 for a sensor distance of a = 1 m.

Generally, the detection is absolutely safe and guaranteed by the system also for arcs of existence borderline conditions until a sensor distance of 2 m if a direct sensor irradiation is given. Detection problems (uncertainties) resulting from total sensor coverage or shadowing may be fully excluded by using 2 sensors in practice.

An increase of the detection system sensitivity may also be achieved by mounting of reflector shields around the sensor heads. Under unfavorable irradiation conditions the detection times can be reduced by shields with an inside reflecting layer. Then a safe detection is given up to sensor distances of 6 m, too.
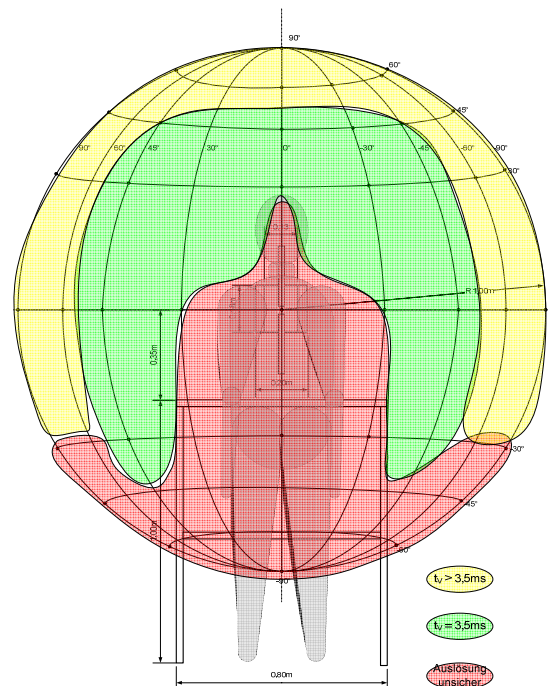

Figure 7: Detection times for a sensor distance a = 1 m for standard parameters (green: minimum delay, yellow: longer detection time, red: detection uncertain)

4. INFLUENCE OF OTHER OPTICAL SOURCES ON THE DETECTION DELAY

The detection system was investigated in further test series with respect to the tripping characteristics

under additional illumination and reflection influences. These tests were made with critical sensor positions (borderline conditions of direct irradiation, distance a = 2 m) and borderline conditions of the arc light intensity. Particularly influences due to

- Intensive background illumination
- Reflection by metal walls
- Extreme reflection by glass mirrors

were analyzed. The optical sensors were equipped with shields and reflectors for finding an optimal sensor construction.

The basic luminance of the sensor surrounding does absolutely not affecting the detection also with an illumination of 5,000 or 10,000 lx (permanent level); the detection delay does not differ from that occurring with normal illumination conditions of 20…700 lx. There are generally no tripping malfunctions. Table 3 shows the detection times resulting from the test series with a background illumination level of 10,000 lx with 3 sensors in different positions in each test. The principle test constellation is shown in Fig. 8 and 9.

Table 3: Detection delay in case of constant intensive background light

Test No.	detection sensor			t_V
	S1	S2	S3	in ms
01	X	X	X	3,30
02	X	X	X	3,33
03	X	X	X	3,31
04	X	X	X	3,48

X – detected;
sensor positions h,v: S1=0,0; S2=30°,0; S3=-30°,0

As mentioned, different sensor constructions were investigated, having only a defined admission zone, for arc radiation to be detected, to optically shield the light sensible sensor heads for preventing tripping due to disturbances by other light sources with permanent illumination levels of more than 100,000 lx or changes of more than 9,000 lx (e.g. due to sun light). The construction shown in Fig. 10 was found to be the optimal variant.

Proved in special additional test series, the shields safely prevent a tripping when the permanent light level at the covered sensor areas is above 100,000 lx (tripping threshold) without endangering a reliable fault arc detection in general. In each of the test cases arcs were detected as desired, the detection times are not or not significantly influenced respectively. Even a reduction of the detection delay may be achieved by using sensor shields with reflecting inner layers and placing the optically sensible sensor heads in the reflector focal point. Also in case of extremely high background illumination the fault arc detection times are in the range of the minimum delay of about 3.5 ms. It must be remarked however that sensor

constructions as mentioned finally increase the risk of detection malfunction for directly entering high-intensity radiation of ambient or other light sources.
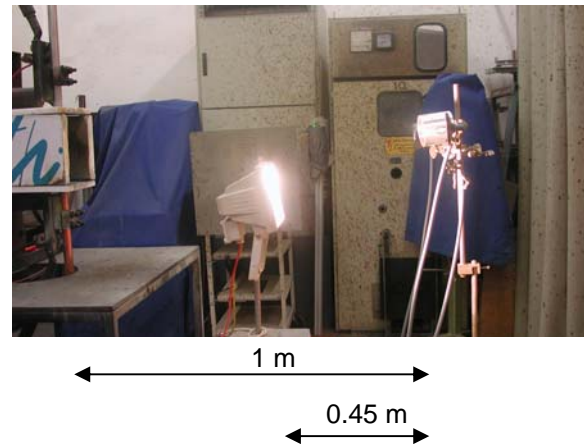

1 m

0.45 m

Figure 8: Test set-up for analyzing extreme background illumination influences

electric arc as light source

2.00 m

sensor with shield

distur-bing light source

optional: reflecting wall (metal or glass mirror)

b

0.10 m
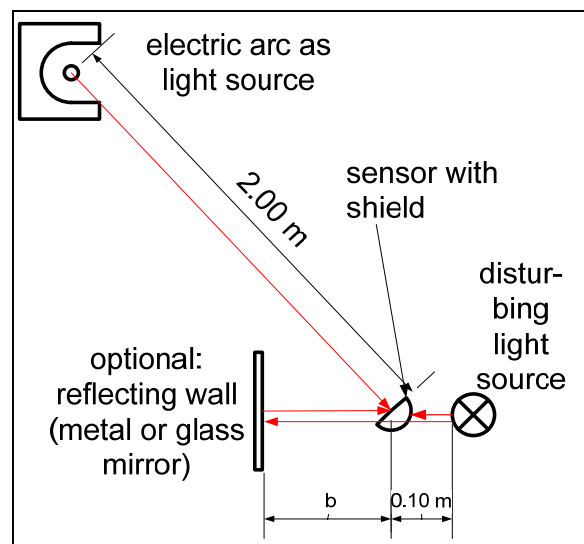
Figure 9: Scheme of the principle test constellations analyzed for optimizing the sensor construction

5. IMMUNITY AGAINST DISTURBING INFLUENCES AND MALFUNCTIONS

According to the sensibility of the detection system (see Section 2) optical sources with light intensities up to 9,000 lx will not be able to cause detection system malfunction. Higher intensities with more than 100,000 lx result in tripping in case of permanent light emission (constant long-term luminance). Sudden luminance changes by more than 9,000 lx will also lead to tripping.

Measurements referring to the immunity of the system against optical or radiation disturbances were conducted. Practically possible optical sources have

been investigated. Test series with halogen lamps, discharge lamps, fluorescent lamps, different hand lamps, flash lights, DC arcs and circuit breaker switching arcs were made, the minimum distances for preventing the detection system tripping were found. Tab. 4 gives an overview on these distances.

Figure 10: Optimized optical sensor with reflector shield (above: with inner reflection layer, below: without inner reflection layer)

In practice system malfunctions can be excluded if the distances to artificial sources such as photo flash lights and powerful xenon lights do not fall below 1 m.

The luminance of lighting installations and lamps at indoor working places ranges between 20 and 5000 lx according to the standard DIN EN 12464-1:2002 [3] , thus there is a very low disturbance probability.

Tests with circuit breakers have shown that there is no detection if the sensors are not closer than about 200 mm to the arc surpressing systems. Tab. 5 shows the results of a test series with a 400 V circuit breaker with a rated current of 1250 A with blow-off characteristic interrupting breaking currents of 4 and 7 kA (rms). Three sensors were used in parallel in a various distance a from the blow-off system in each test. No sensor indicated the switching arc in the series.

Table 4: Minimum distances of artificial light sources for preventing disturbances

Type of artificial light source	Minimum distance a in mm
Photo flash light LFI* 9	-
Photo flash light LFI* 21	100
Photo flash light LFI* 45	300
Photo flash light LFI* 60	2400
Pocket lamp: Krypton light 2 W	-
Hand LED lamp	-
Laser pointer	200
Halogen reflector lamp 20 W	200**
Halogen spot light 500 W	(100)550**
Standard fluorescent lamp 500 lx	-
Fluorescent hand tube light 8 W	-
Xenon lamp with optic 400 W	1500

*LFI – light flash index (LFI is < 20 for normal photo flashs; LFI > 20 means special high intensity flashs, LFI > 45: professional flash lights)
**in case of switching-on

Table 5: Results of sensor immunity tests with a 1250 A LV circuit breaker

TEST No	Sensor distance a in mm	Breaking current (rms) in kA	detection					
			Sensor 1		Sensor 2		Sensor 3	
			yes	no	yes	no	yes	no
01	100	4		X		X		X
02	100	4		X		X		X
03	100	4		X		X		X
04	100	4		X		X		X
05	50	4		X		X		X
06	50	4		X		X		X
07	50	4		X		X		X
08	50	4		X		X		X
09	10	7		X		X		X
10	10	7		X		X		X
11	10	7		X		X		X
12	10	7		X		X		X
13	50	7		X		X		X
14	50	7		X		X		X
15	50	7		X		X		X
16	50	7		X		X		X

In general in indoor applications of the detection system malfunctions of system tripping can be excluded, the detection system may be used indoor without any further restrictions.

Outdoor significantly higher light intensities occur due to direct and indirect sun radiations particularly. Hence, investigations were made regarding the construction of the optical sensors and the

optimization of the necessary sensor shields. By means of the distinguished extensions in the sensor construction described above (special shielding and reflecting constructions for surpressing disturbance light and amplification of arc light receiving) ways to improve the sensor immunity and to shorten the tripping delay were tested and evaluated under critical detection conditions (low arc light intensity, sensor positioning at the limits of direct exposure, high background luminance level, disturbance light reflections) also for outdoor conditions. On these investigations it will be reported later at another place.

The risk of unintended tripping can be kept small or in acceptable limits by paying attention to a couple of handling restrictions. Radiation to the optical sensible sensor parts by direct luminance or caused by reflection with more than 9,000 lx from artificial light sources and sun light has to be prevented. This can be reached by definition of minimum distances of the lighting equipment, by positioning of the sensors (height, direction) and by protection walls.

6. SUMMARY

The optical arc detection system investigated shows very high detection reliability. It guarantees very short detection times. There is no risk of malfunction (unwanted tripping) when used indoor. The necessary high immunity (safety against disturbances) may be achieved by means of working instructions which forbid a direct exposure of the optically sensitive sensor heads by artificial light sources with short distances.

With this, the indoor application of the protection system is possible without any restrictions. The arc detection and extinction times achievable and provided by the system guarantee that the remaining thermal arc consequences are wide below the tolerance limits of personal protection (personal injury) and become extremely small.

The application of the protection system is also possible outdoor. Investigations carried out show disturbing light influences to be preventable by working walls to be put on, too. This will be reported about separately.

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