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Arc Faults in Medium-Voltage Switchgear and
Low-Voltage Switchboards
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Arc Faults in Medium-Voltage Switchgear and Low-Voltage Switchboards

An arc is created by ionization of a gas (normally air) by means of an electric discharge between electrodes of different potential or phase angle, or between an electrode and earth. The term "arc discharge" is also common. If this effect is caused by a fault, such as a short circuit inside a switchgear or switchboard, this is referred to as an arc fault. Whereas the generation of an arc fault in low-voltage systems often requires a short-circuit by direct contacting, not observing a minimum clearance in air between the live parts of a switchgear will suffice to cause such a fault under medium-voltage conditions.

The probability that an arc fault occurs in a switchgear or switchboard is very low, but must not be neglected. As empirical values, 10^{-4} incidents per annum are expected for air-insulated switchgear, and 10^{-5} incidents p. a. for gas-insulated switchgear. This means that, statistically speaking, an arc fault is caused in one of 10,000 (air-insulated) panels in a year, or in one of 100,000 (gas-insulated) panels.

In low-voltage systems, approx. 5 % of electrical accidents result from an arc fault. A difference is made between serial and parallel arcs.

A serial arc has low current and power values, in the range of load currents. It represents a high fire risk for the switchboard and usually develops to a parallel arc. In contrast, a parallel arc reaches high current and power values, in the range of short-circuit currents, and involves a high danger for persons and equipment. Nearly 95 % of all arc faults are parallel arcs and serial arcs developing to parallel arcs.

The reasons for the generation of an arc fault in a switchgear or switchboard, also called "internal fault", may be as follows:

- Material or functional faults of devices (e.g. insulation faults, defective contact points, installation errors)
- Incorrect rating and dimensioning (e.g. abruptly blowing fuses)
- Overstress, pollution, humidity
- Handling errors and inattention during operation and work (e.g. non-permissible working under live conditions)
- Small animals and other foreign objects (e.g. forgotten tools) which get into the interior of the switchgear or switchboard
- Incorrect execution of cable connections.

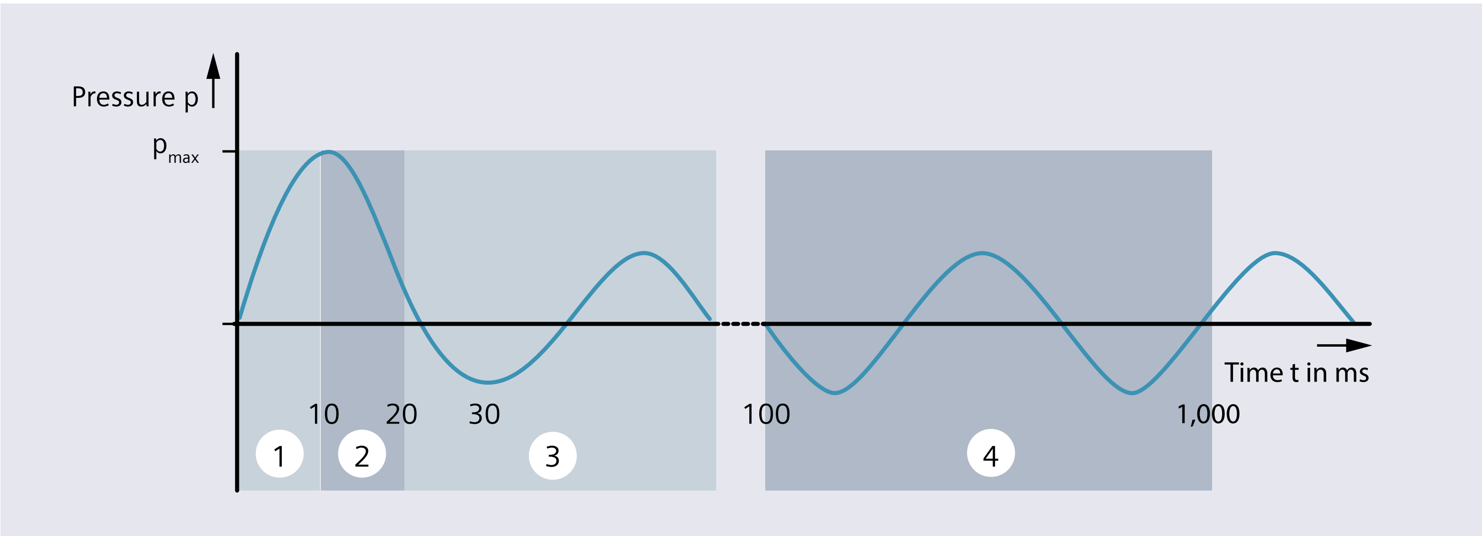
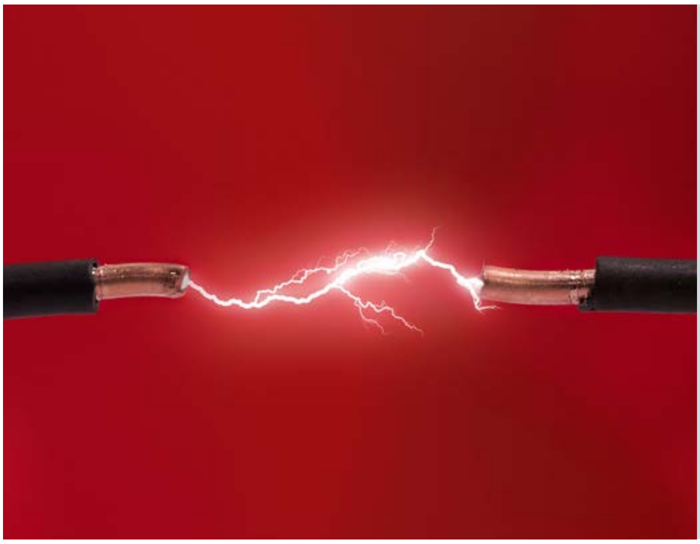


Fig. 1: **Pressure development over time in case of an arc fault**

When a gas plasma is created, temperatures of approx. 10,000 °C may be produced (even up to 20,000 °C at the point of outlet), thus vaporizing the material at the point of outlet. This improves conductivity and the current flow is increased, which may, in turn, result in a further temperature increase. The process is described in four phases as shown schematically in Fig. 1.

1 Compression phase (with maximum overpressure)
2 Expansion phase (declining pressure)
3 Emission phase (gas emission)
4 Thermal phase (emission of the heavier metal and insulating material vapors).

Arc fault tests performed with a panel demonstrated a pressure of approx. 10 t/m^2 for a given area load.



Protection of persons and equipment

Even arc faults with a low energy input can have a considerable impact on switchgear availability and personal safety. A value of 100 kJ is considered a limit for the arc energy. Below this value, the switchgear or switchboard does not incur irreversible damage and will be ready for reconnection within a short period of time after some maintenance work. According to Schau, Haase [1], persons with "standard-conforming" working clothes (as defined in the standard series IEC 61482 or NFPA 70E) will not be affected by impermissible impacts, i.e. second-degree burns, up to an arc fault energy of 250 kJ.

To continuously improve switchgear availability and personal safety, factory-assembled and/or type-tested switchgear/switchboard types are almost exclusively used in medium-voltage and low-voltage systems today. Accordingly, the associated standards have also been developed further over the last decades. In contrast to the former voluntary tests regarding the protection of persons in case of an arc fault under operating conditions, which left a wide margin for interpretation, tests are harmonized today according to the state of the art.

Apart from the relevant product standards for medium-voltage switchgear and low-voltage switchboards, the installation standards

- IEC 61936-1 for high/medium voltage and
- IEC 60364 series for low voltage

must be taken into account to ensure the protection of persons and equipment.

Pressure load of buildings in the event of an arc fault

For power installations with a rated voltage exceeding 1 kV in buildings, IEC 61936-1 requests the building structure to withstand the internal pressure generated by an arc fault. According to this, the electrical service room for medium-voltage switchgear and transformers must always be included in the protection measures to be taken against the effects of an arc fault:

- A calculation of the static or dynamic pressure load, from which an architect or structural engineer may recognize the stress on building structures, is recommended
- The service room must be equipped with pressure relief outlets of sufficient cross-section or with a pressure relief duct.

Siemens provides two calculation methods to establish rough guide values for the pressure load and/or the pressure relief outlets during the planning phase.

Estimation of pressure effects according to Pigler

A simple method for rooms up to 50 m³ is provided by the estimation according to F. Pigler [2]. The corresponding calculation can be requested from your Siemens TIP contact partner for applications with Siemens medium-voltage switchgear types 8DJH, 8DJH Compact, and 8DJH 36. The static overpressure on the building structure is determined based on the room volume, the area of the free relief cross-section, the short-circuit current, the panel type, and a possible additional pressure relief through an absorber system.

The findings of a series of pressure calculations with variable marginal conditions (for example: room dimensions, size of the pressure relief outlet, use of pressure-reducing absorbers at the switchgear), provide an overview of the pressure behavior with regard to the variation of these marginal conditions.
Figs. 2 and 3 show the pressure behavior depending on the cross-section of the pressure relief outlet for a given room volume and short-circuit current (Fig. 2 for a system with pressure absorber, i.e. relief into the switchgear room; Fig. 3 without pressure absorber, i.e. relief into the double floor).

8DJH (24 kV, individual panels, with air-insulated metering panel) with pressure absorber, with relief into the switchgear room

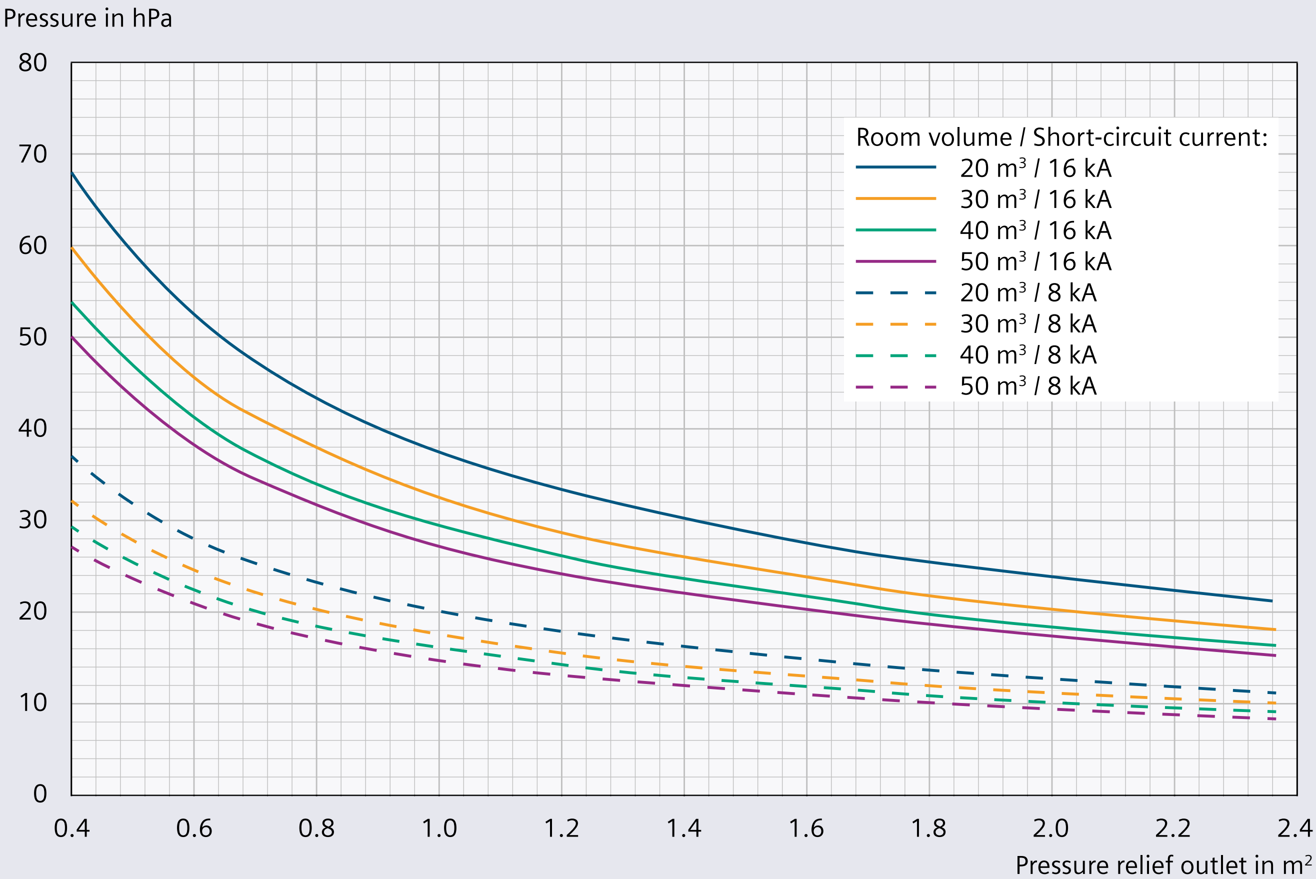


Fig. 2: **Overpressure behavior of a Siemens 8DJH switchgear assembly with relief into the switchgear room, with pressure absorber**

For the same switchgear type, but without air-insulated metering panel, the overpressure with pressure absorber is only about 24 % of the values of Fig. 2 as an average, and only about 35 % of the values of Fig. 3 if there is no pressure absorber. This demonstrates that the metering panel is also a critical item with regard to the pressure development of arc faults.

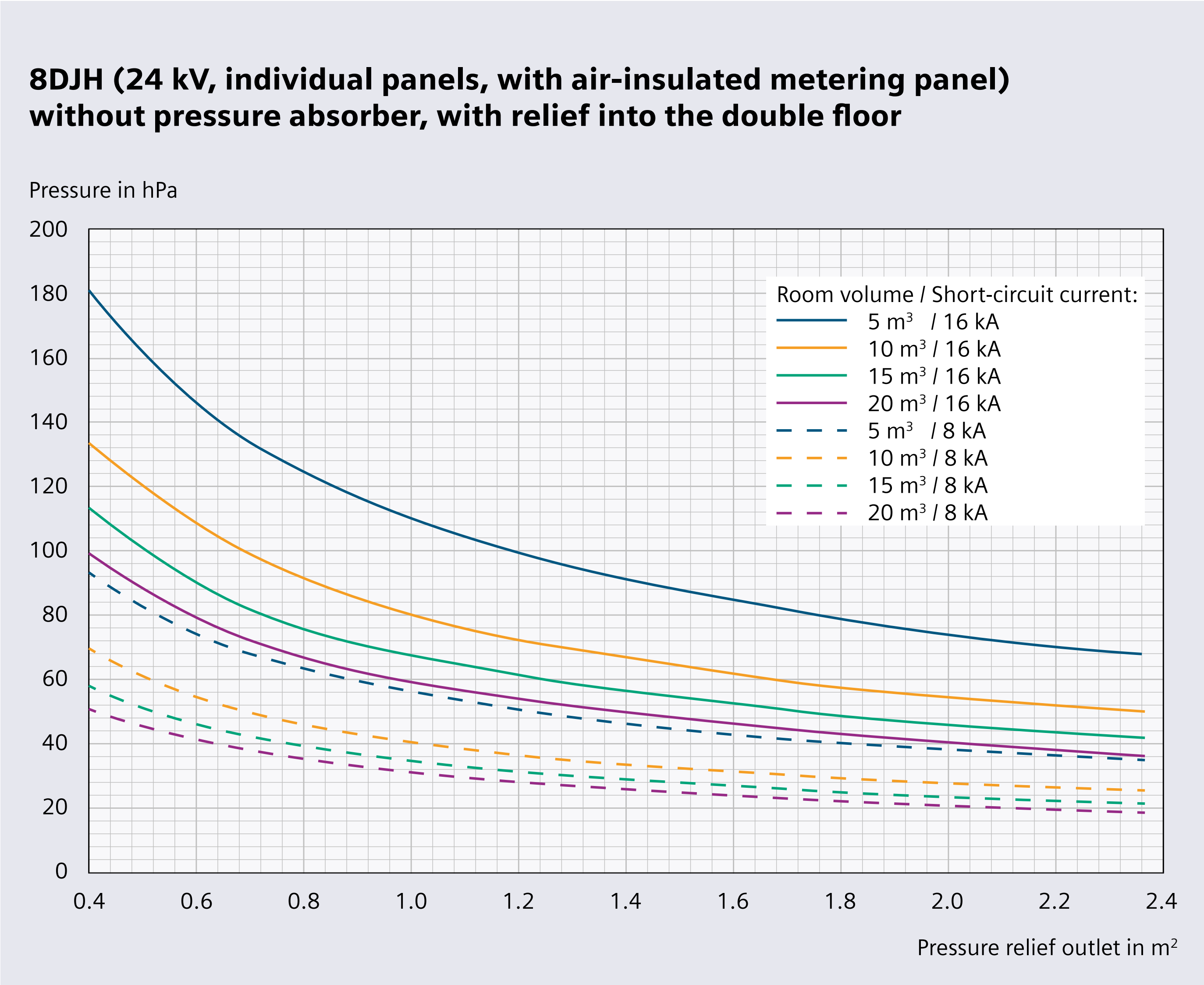


Fig. 3: **Overpressure behavior of a Siemens 8DJH switchgear assembly with relief into the double floor, without pressure absorber**

Finite elements simulation of pressure load in the event of an arc fault

Although the incidence of an internal fault (with an arc fault) is very unlikely in type-tested air- or gas-insulated switchgear, the consequences of such a fault may be severe for the operating personnel as much as for the room itself. For this reason, appropriate pressure relief measures may have to be provided during switchgear and room planning. To do so, there are various options, such as pressure relief outlets, pressure relief ducts, or absorbers.

With the aid of ultra-modern FE (finite elements) methods, pressure calculations can be performed in the entire spatially resolved room over the entire burning time of the arc fault. Siemens offers the service of a numerical calculation on the basis of a 3D volume model, where the real installation of the switchgear/switchboard, pressure development, reflection, and arrangement of the pressure relief outlets is taken into account (costs amount to 3,000 € and more depending on outlay; please refer to your TIP contact partner for such requests).

Various pressure load scenarios can be calculated for specific switchgear/switchboard types, short-circuit currents, and places of installation. Thus, the customer benefits from extended planning security and a cost-optimized solution.

The flow conditions are defined as marginal conditions. On the one hand, these are the steel sheets of the switchgear/switchboard, and on the other hand, the absorber sheets to be flown through. At last, the pressure relief outlets in the switchgear room are defined (see Fig. 4). The model even allows to calculate a fully enclosed room or consider pressure relief outlets with a pre-defined pickup pressure. As a result, the model supplies the pressure increase and the flow conditions at any point of the finite elements grid over time.

Additionally, the pressure distribution on the walls of the switchgear room can be shown as a contour plotting at a certain point of time (see Fig. 5). A higher pressure in the range of a factor of five or more may be expected if conventional air insulation is used in the switchgear design as against gas insulation with absorber.

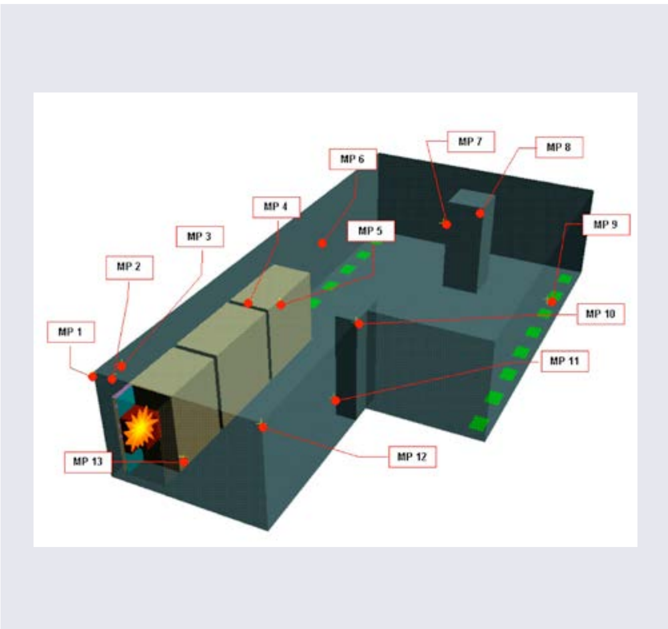


Fig. 4: **Example of a view of the switchgear room with user-selected measuring points**

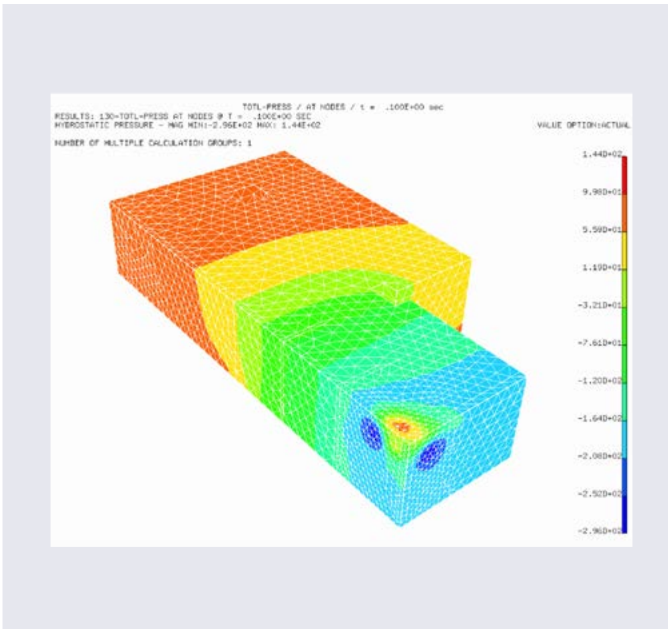


Fig. 5: **Contour plotting of a simulation calculation at 0.1 s**

Pressure effects

A pressure increase in the event of an arc fault must be taken into consideration for the planning of a building, or else damage or destruction of the building structure would be possible. Tab. 1 contains guide values for the permissible static pressure in buildings dependent on the wall material in new condition.

Besides the building material, dimensions, thickness and restraint pressure of the wall in the building structure also play an important part for the pressure load. The structural engineer must design the building for the calculated pressure, since there are no binding or generally valid values available. For guidance, some values from report [3] are listed in Tab. 2 as an example.

Type of wall	Permissible overpressure in the room
Gypsum board	< 10 hPa
Brick wall without side connection (e.g. between concrete pillars)	10 hPa
Brick wall with reinforcing iron, wall thickness ≥ 24 cm (e.g. between concrete pillars)	25 hPa
Ready-mixed concrete parts	50 hPa
Cast-in-situ concrete	> 70 hPa
Concrete room cell	130 hPa

Tab. 1: **Load-bearing capacity of different wall materials in case of overpressure [1]**

Consequence	Peak overpressure (hPa = mbar)
Direct personal injury	
Unpleasant bang effect of deep frequency	1.5 hPa
Very loud bang	3 hPa
People are blown over	10 hPa
Pressure-related limit value for damage effected by bursting and projected parts	15 hPa
Lower threshold of tympanic membrane rupture	175 hPa
Damage to the tympanic membrane	300 hPa
Lower threshold for pulmonary damage	850 hPa
Lower threshold for severe pulmonary damage	1,850 hPa
Lower lethality threshold	2,050 hPa
Glass panes	
Occasional breakage of large panes under tension	2 hPa
Glass breakage owing to sound waves	3 hPa
Breakage of small panes under tension	5 hPa
Destruction of 10 % of window panes	10 hPa
Destruction of 50 % of window panes	30 hPa
Destruction of 75 % of window panes	50 hPa
Damage to building	
Damage on window frames, doors and roofs	5 hPa
Minor damage on roofs	20 hPa
Destruction of roofs and walls of wooden houses	60 hPa
Little to medium damage on residential buildings	120 hPa
Destruction of brick walls	200 hPa
Medium to severe damage on residential buildings	350 hPa
Almost complete destruction of normal buildings	400 hPa
Destruction of multi-story buildings, destruction of 50 cm brickwork	500 hPa
Damage to infrastructure	
Dented sheet-steel plates	75 hPa
Slightly deformed steel frames of skeleton buildings	95 hPa
Ruptured oil tanks	215 hPa
Destruction of reinforced concrete walls	350 hPa
Empty rail cars thrown over	460 hPa
Loaded freight cars thrown over	600 hPa
Loaded freight cars destroyed, 99 % damage to horizontally stored pressurized containers, chemical reactors, and heat exchangers	750 hPa

Tab. 2: **Effects as a function of the overpressure magnitude [3]**

Testing of a low-voltage switchboard

The Technical Report IEC/TR 61641 describes a particular test for low-voltage switchboards, which is not really a binding prescription in the sense of a design verification or a type test, but recommended as it improves personal safety significantly. The design verified switchboards SIVACON from Siemens meet the corresponding requirements.

The criteria for assessment of the test under conditions of arcing with regard to personal safety are as follows:
- Correctly secured doors, covers, etc. do not open
- Hazardous parts (e.g. large or heavy parts, parts with sharp edges) of the switchboard cannot fly off
- No holes are produced in freely accessible sides of the enclosure
- Vertically arranged indicators, which have been particularly mounted, do not ignite (exception: indicators for the detection of the thermal effect of gases, which are ignited by burning paint coatings or adhesive labels, must be excluded in the assessment)
- The protective conductor circuit for accessible parts of the enclosure is still effective.

For switchboard safety, the following must be additionally complied with:
- The arc fault is limited to the defined area, and there is no reignition in the adjacent areas
- Emergency operation of the switchboard is possible after the fault has been cleared and/or affected functional units have been disconnected or removed. This must be verified by an insulation test with a value of 1.5 x rated operational voltage for the duration of one minute.

Depending of the network configuration, the extent of damage caused by an arc fault can be compared to that of medium-voltage switchgear. Nevertheless, pressure calculations in low-voltage systems as well as for transformer rooms are not yet common practice, but one should be aware of the danger that can also arise in these cases. For this reason, it is strongly recommended to observe the installation information for the respective switchboard type. For the transformer room there is a Siemens tool available, which is briefly described in the following.

Testing of medium-voltage switchgear under conditions of arcing

A successful type test of medium-voltage switchgear also requires an internal arc classification (IAC) in accordance with IEC 62271-200. The classification distinguishes the following:
- Accessibility:
  - A Access for authorized personnel only
  - B Public access (meaning a higher test level)
- Classified, accessible sides of the switchgear:
  - F Front (front side)
  - L Lateral (side wall)
  - R Rear (rear wall)
- Test current and duration.

Example: Internal arc classification IAC AR BFL 25 kA 1 s

The specification means that the rear side may only be accessed by authorized personnel, whereas the front and lateral sides are freely accessible. The arc fault test was carried out with a test current of 25 kA for a duration of one second.

Remark:

Medium-voltage switchgear in electrical service rooms is generally tested according to accessibility type A, to which only qualified personnel instructed in electrical engineering have access. Only complete, factory-assembled substations such as transformer / load center substations or concrete substations are tested for type B.

The criteria for assessment of the test under conditions of arcing with regard to personal safety correspond to those for low-voltage systems.

Configuration of a transformer room

Like in medium-voltage switchgear or low-voltage switchboards, there also is the hazard of an arc fault in the transformer room. Compared to switchgear rooms, the pressure increase can be much higher here, since the space in the transformer room is often much more confined. The call for an appropriate verification of the pressure increase in the event of an arc fault is pushed by surveyors.

Siemens has developed a tool (Fig. 6) for the calculation of the pressure increase in the event of an arc fault, which is based on the estimations of F. Pigler [2] and in-house experience. When Siemens GEAFOL transformers are used, such a calculation can be performed by means of SITRATO (part of the SIMARIS Suite). If you need support, please refer to the Siemens TIP contact partners (www.siemens.com/tip/contact). Besides a graphical evaluation of the pressure development (Fig. 7), the data on ventilation and pressure increase is output in the documentation.

The following characteristics or physical quantities are useful for the planning of an electrical installation in SITRATO:

- EMC limit values and correspondingly necessary clearances
- Estimation of the power reduction for standard transformers due to harmonics
- Efficiency of a transformer for selecting a loss-optimized working range.

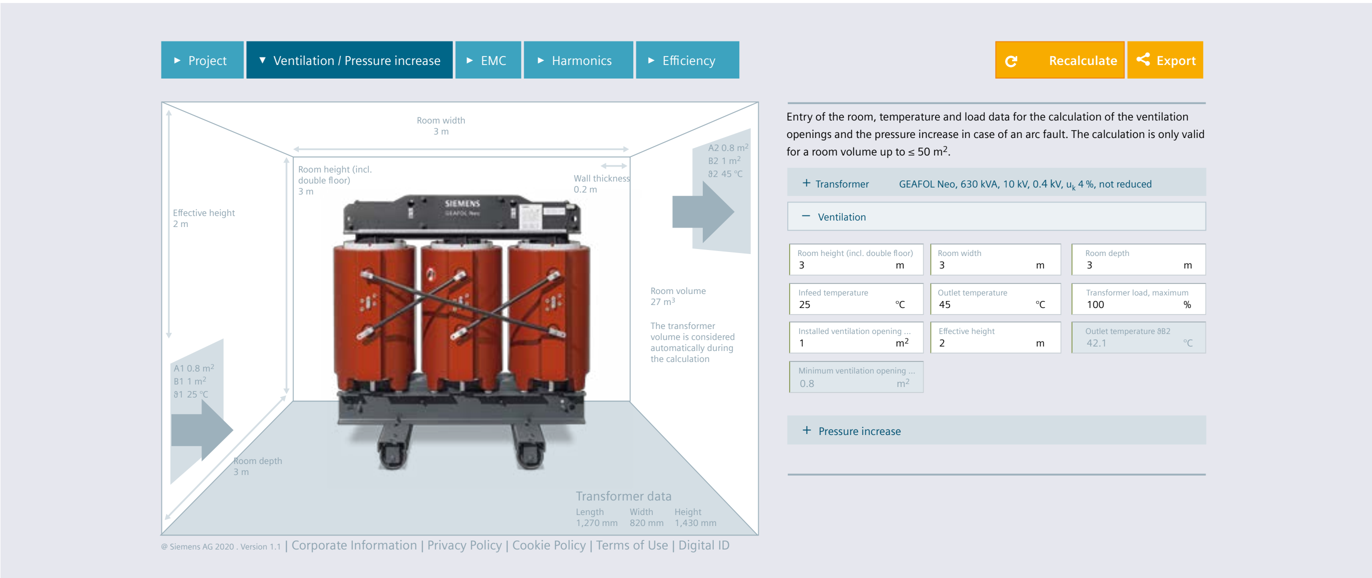


Fig. 6: **Screen view of the calculation tool SITRATO for a transformer room**

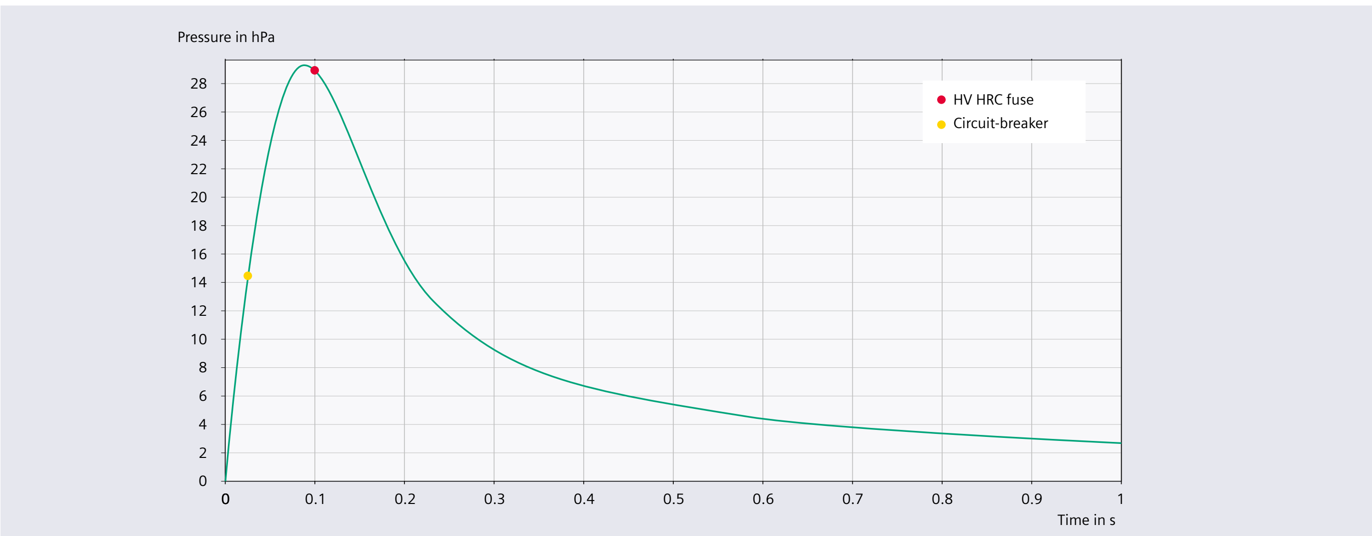


Fig. 7: **Pressure development for the sample calculation of a transformer room**

Protection in the event of an arc fault in switchgear and switchboards

Two principles have prevailed in practice for the protection in the event of an arc fault. On the one hand, the passive arc fault protection, which is based on prevention. This means that the probability of occurrence on an arc fault is reduced to a minimum at any time, or that the development of an arc fault can even be prevented. The passive protection concept is frequently applied in low-voltage switchboards such as SIVACON S8.

On the other hand, the active arc fault protection has increasingly been enforced in the last years. Its principle assumes that an arc fault can occur, and that it must be detected and extinguished by active means as quickly as possible, i.e. within a few milliseconds, in order to minimize the extent of damage. The active arc fault protection is offered by various manufacturers as an autonomous system. The individual systems differ in details, but the functionality is mostly based on the same principle. At Siemens, active arc fault protection systems are used in both low-voltage switchboards (SIVACON S8) and air-insulated medium-voltage switchgear (NXAIR).

The protection principle to be applied in low-voltage switchboards depends on several factors:

- Economic aspects, such as investment and servicing costs
- Availability of the switchboard and downtimes with consequential costs
- Reliability of the protection principle and the materials or equipment used
- Requirements on personal safety
- Requested scope of protection for the switchboard areas
- Positive or negative experience.

Principle of the passive arc fault protection

In a passive arc fault protection system, the use of insulating materials (e.g. Teroson), which are wrapped around live bare conductors, of covers, shutters and similar parts prevents the development of parallel arcs (between two active conductors or between an active conductor and the neutral conductor). Depending on the requested availability, this protection can be applied in several steps, from limiting the effects of an arc fault in a cubicle, through their limitation to a functional compartment, and up to their limitation to the place of origin. Examples hereto are given in Fig. 8.

Fig. 8: **Passive system to prevent an arc fault, with insulated busbar, cubicle link, incoming and outgoing feeders, and withdrawable MCC**

A basic precondition for the safety and quality of the passive system is the professional installation of the insulation. For Siemens switchgear and switchboards, there is a special installation instruction available that also specifies the property and arrangement of the materials (see Fig. 9).

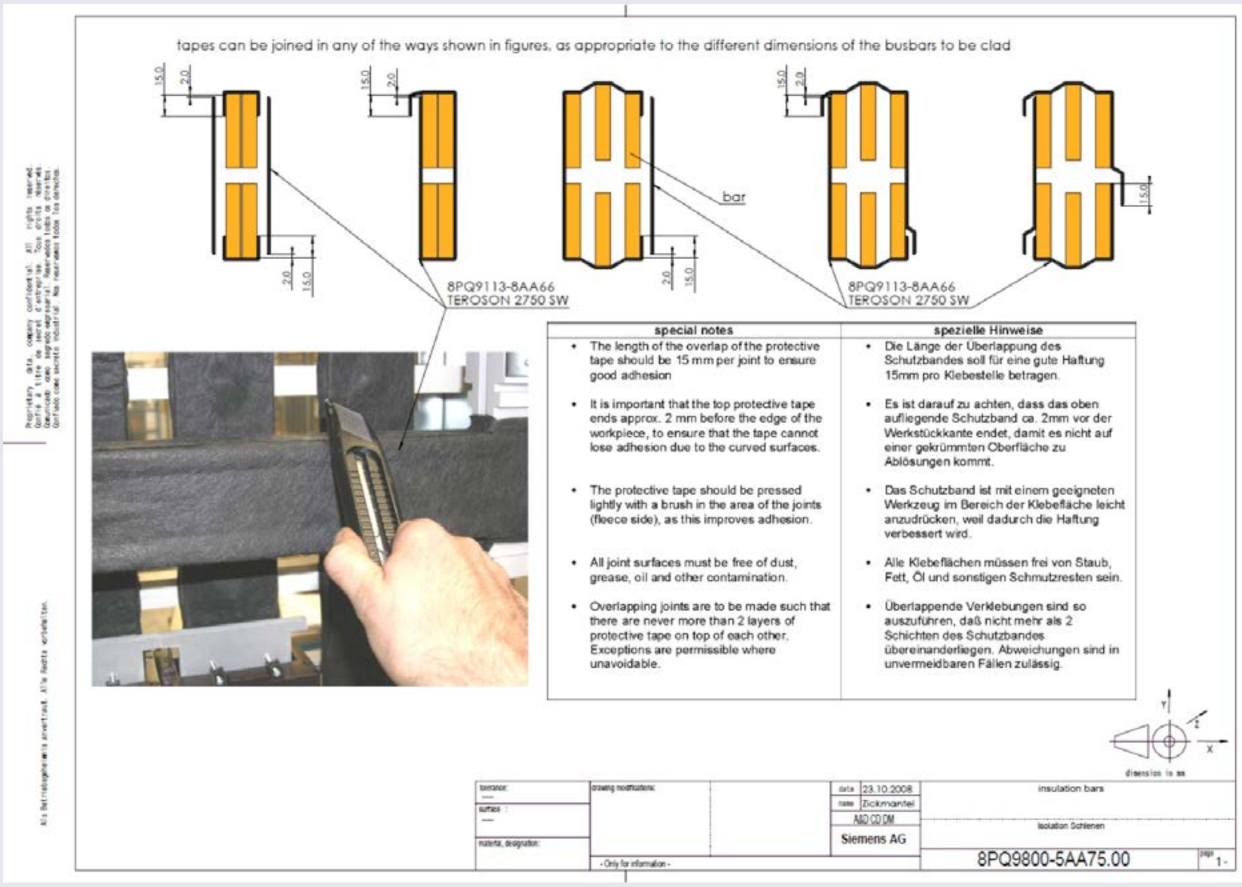


Fig. 9: **Work instruction for the installation of a passive system for Siemens switchgear and switchboards**

Principle of the active arc fault protection

The active arc fault protection systems which are currently available on the market require two criteria for correct operation:

- Light criterion:
  When an arc fault occurs, e.g. due to an insulation fault, improper work at the switchgear/switchboard, or small animals, a lightning flash occurs, which is detected by a point sensor or a fiber-optic cable (line sensor).
- Current criterion:
  Current transformers register a steep current increase.

Both criteria must be fulfilled if the detection and tripping device (IACD: Internal Arc Fault Device) shall recognize an arc fault and initiate a tripping. Fig. 10 shows the general functional principle of an active arc fault protection.

Within just a few milliseconds, the AQD (Arc Quenching Device) is tripped, which results in a low-resistance current path through which the fault or short-circuit current flows now, thus extinguishing the arc. This current path is maintained until the incoming circuit-breaker has interrupted the short-circuit current. The minimum time during which the arc fault is burning limits the damage impact on persons and equipment extremely. Siemens uses the portfolio shown in Fig. 11 in their medium-voltage switchgear and low-voltage switchboards.

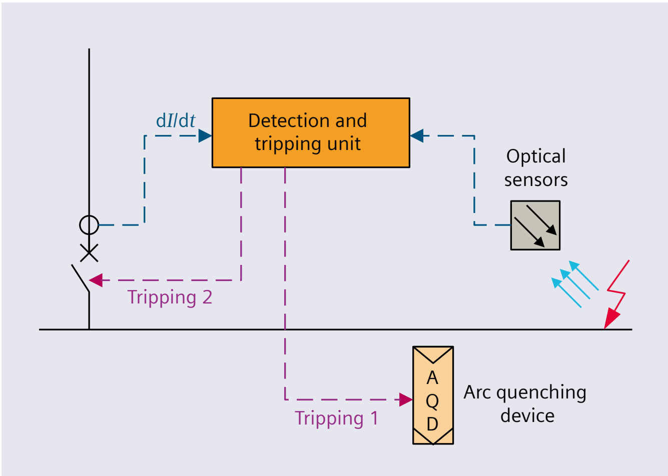


Fig. 10: **General functional principle of an active arc fault protection**

Fig. 11: **Portfolio of the active arc quenching devices from Siemens**

Live working

Working on or close to electrical installations always involves the hazard of an arc fault endangering persons in close proximity. An arc fault can not only develop from a short circuit, but also when live parts are disconnected; for example, when fuses are pulled out. The risk of a thermal hazard to persons due to an arc fault can be reduced by personal protective equipment (PPE).

The effects of an arc fault are mainly determined by the electric arc energy W_{arc} and the distance a between the person and the arc. W_{arc}, in turn, is determined by the active power of the arc P_{arc} and the arc duration t_{arc}.

The incident energy E_i identifies the quantity of heat caused by an electric arc per surface unit at a defined distance to the electric arc. The incident energy E_i is linearly proportional to the arc energy W_{arc}, but the transmission function f_T depends non-linearly on multiple factors of influence:

$$E_i = f_T \cdot W_{arc} \qquad \text{with } f_T = f(x_v)$$

Here, the parameters x_v for v = 1 to 6 are:

- x_1: Distance a to the axis of the arc (approximately inversely proportional to the square of the distance)
- x_2: Spatial environment of the arc (open, enclosure, walls, etc.)
- x_3: Electrode configuration (vertical, horizontal, barriers, 2-pole/3-pole)
- x_4: Electrode distance d
- x_5: Electrode material
- x_6: Voltage and current level of the electrical system (network).

In the context of arc faults, second-degree skin burns are considered a critical limit for the human body. In the IEEE 1584 standard, this limit is defined without protective equipment at an incident energy of 50 kJ/m² (1.2 cal/cm²). In contrast to this, Stoll-Chianti [5] have defined a more differentiated limit curve as a function of the exposure time t_i:

$$E_i = 50.204\ \text{kW/m}^2 \cdot t_i^{0.2901}$$

The example of Fig. 12 illustrates the influence of the PPE on the impact of an arc by means of the resulting temperature rise and the relation to the Stoll curve. The temperature rise is proportional to the incident energy [4]

$$E_i = \text{f(sensor)} \cdot \Delta T_{max}$$

whereby the factor f(sensor) depends on the properties of the calorimeters used for the temperature measurement. The illustration shows that tested PPE can prevent second-degree skin burns, which would probably not be the case without a protection (sensor 1).

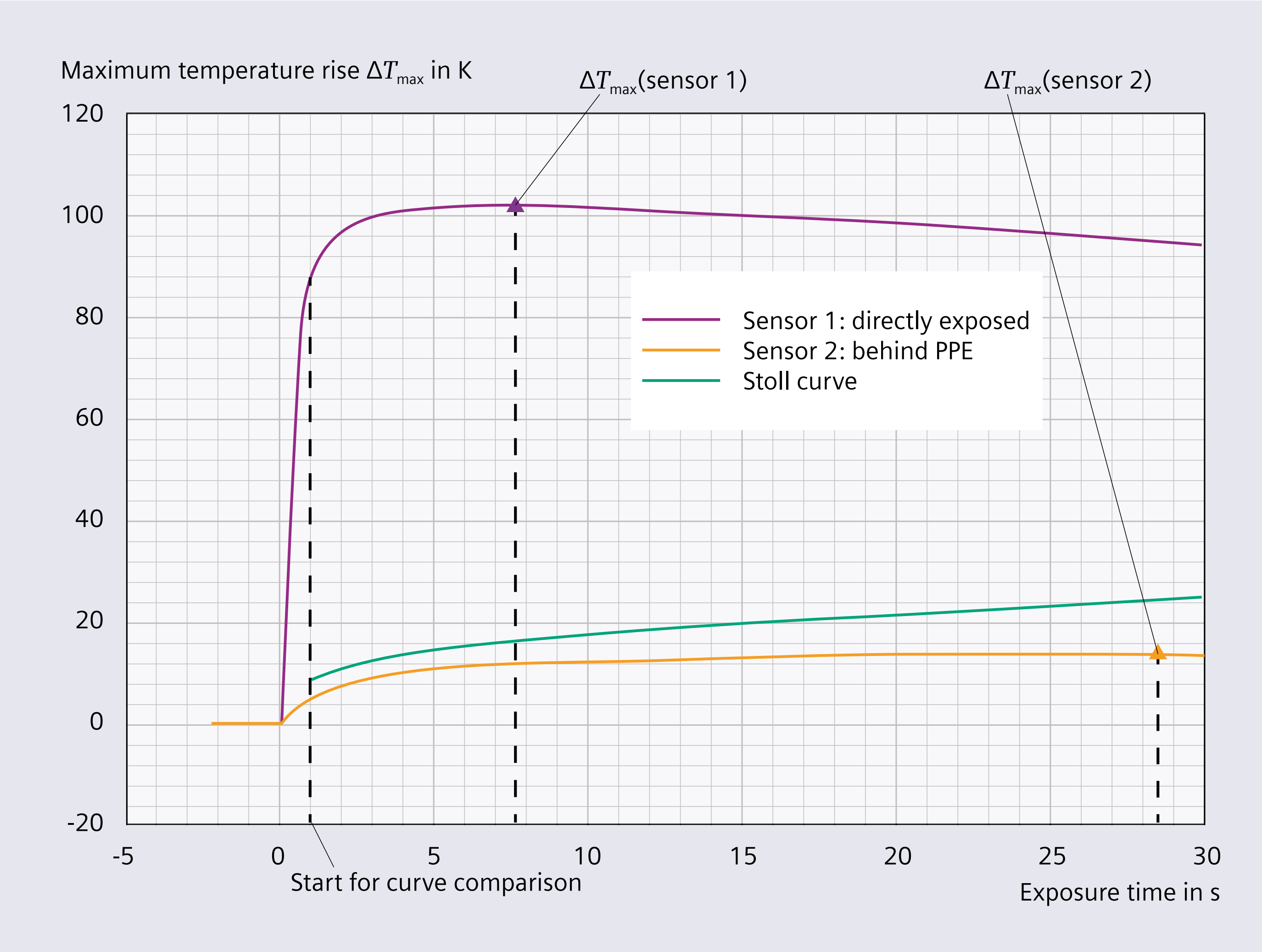


Fig. 12: **Temperature developments during an electric arc test (example from [4], where sensor 1 is directly exposed and sensor 2 is located behind the PPE)**

Standardized test methods for PPE products

According to the IEC standards, there are two test methods for the PPE:

- Arc rating test acc. to IEC 61482-1-1
- Box test acc. to IEC 61482-1-2.

With the arc rating test, the arc characteristics

- ATPV: arc thermal performance value
- EBT: breakopen threshold energy
- ELIM: incident energy limit

of materials, clothing and clothing combinations are determined under laboratory conditions using an open arc. An arc is generated, which can spread its thermal radiation in all directions in an open construction. The test energy is varied step by step by changing the arc duration with a constant prospective test current (8 kA). For example, the incident energy assumed to cause second-degree burns with a probability of 50 % – without rupture of the clothing – is determined as the ATPV of the protective clothing.

In contrast to the arc rating test, the box test uses a directed test arc in order to obtain a classification for the protective clothing with regard to the two protection classes (Tab. 3) defined in the IEC 61482-1-2. Class 1 corresponds to a basic protection, and class 2 stands for a higher protection level.

The box test is executed with constant test parameters and a constant prospective test current of 4 kA (class 1) or 7 kA (class 2). The arc is ignited in a box with only one opening (to the front). Thermal radiation, convection and metal spatters are thus directed towards the "person".

The test levels (test current) in the box test do not represent the application limits of the PPE. The actual protection effect can thus also be provided at higher energies, but it is not tested. The test result only means:
Test for class 1 or 2 passed -> yes / no.

The box test and the arc rating test are not comparable, as they are based on different setups and test conditions.

	Arc energy		Incident energy	
	Mean value W_{arc}	Permissible deviation	Mean value E_{i0}	Permissible deviation
Class 1	168 kJ	± 17 kJ	146 kJ/m^2	± 28 kJ/m^2
Class 2	320 kJ	± 22 kJ	427 kJ/m^2	± 39 kJ/m^2

Tab. 3: **Arc energy and incident energy for the protection classes of PPE according to IEC 61482-1-2**

Calculation of the incident energy acc. to IEEE 1584

The IEEE 1548 standard defines an empirical model which can be used as a basis to determine the incident energy of an arc fault. For risk evaluation, the arc fault limit is defined as the distance to the arc fault location where the incident energy is 50 kJ/m² and second-degree burns are thus not expected anymore. Marginal conditions of the model:

- Line voltage between 208 V and 15 kV
- Frequency 50 Hz or 60 Hz
- Terminal short-circuit current (I_k''):
  - 500 A to 106 kA for $U_n \leq 600$ V
  - 200 A to 65 kA for $U_n > 600$ V
- Conductor spacing:
  - 6.35 mm to 76.2 mm for $U_n \leq 600$ V
  - 19.05 mm to 254 mm for $U_n > 600$ V
- Working distance 305 mm as a minimum
- Correction factors for enclosure dimensions deviating from those of the box test
- Different arrangement of electrodes or conductors:
  - Arrangement of conductors in free air: horizontal (HOA) or vertical (VOA) → calculation for PPE according to IEC 61482-1-1
  - Arrangement of conductors in an enclosure: horizontal (HCB), vertical (VCB), or vertical with termination or insulating plate (VCBB) → calculation for protective equipment according to IEC 61482-1-2.

For the evaluation of risks in the event of an arc fault occurring in a switchgear/switchboard, all possible fault locations within the switchgear/switchboard and all panels/cubicles must be determined, and the incident energies have to be determined according to the configurations and parameters.

The procedure to determine the incident energy at a fault location can be roughly described as follows:

1. Determination of all 3-pole terminal short-circuit currents, taking into account all possible network switching states, shares of motorized feedbacks, parallel operation of energy sources, etc. (in analogy to IEC 60909-0: Calculation of currents in three-phase AC systems)
2. Determination of geometric quantities:
   - Conductor spacing
   - Enclosure size, including correction factors for deviating quantities to the box test
   - Determination of the arrangement of conductors at the fault locations
   - Determination of the working distance
3. Determination of the mean an minimum arc fault current for all operating states based on the data from item 1 and 2.
4. Determination of the arc fault burning duration depending on the protection device and the currents determined in item 3.
   - The upper tolerance band of the tripping characteristic of the protection device is to be used; otherwise, the internal times of the switching devices and further tolerances of the protection device must be considered
   - In the case of fuses, the burning duration set must not be lower than 10 ms
5. Determination of the incident energy, and thus of the arc fault limit.

Based on the empirical formulas in the IEEE 1548 with the multiple factors to be selected and the necessary knowledge of the switchgear/switchboard setup, in particular regarding the arrangement and spacing of conductors, the procedure is relatively complex and complicated.

Determination of the arc energy in accordance with the DGUV information 203-077

To select the correct PPE for live working, it is also possible to apply the procedure described in the information 203-077 [6] of the German Social Accident Insurance (DGUV). In this context, the arc energy W_{arc} to be expected in the event of an arc fault is compared to the protection level $W_{arc,PPE}$ of the intended PPE.

An estimation of the arc energy, based on the box test according to IEC 61482-1-2, is presented in [6]. With this method, the arc fault hazard shall be easily determined with a sufficient safety margin. In addition to this, Fig. 13 gives an overview of the individual steps in a simple process diagram on the next page.

The arc energy W_{arc} is the product of the arc power P_{arc} and the arc duration t_{arc} = short-circuit duration t_k:

1. The short-circuit duration t_k
   is determined by the overcurrent protection device at the minimum arc current $I_{arc,min}$. As the worst case, the minimum three-phase short-circuit current $I''_{k3,min}$ is selected. Due to the current-limiting effect of an arc fault, the following applies:
   $I_{arc,min} = I''_{k3,min} \cdot k_B$
   with a current-limiting factor $k_B = 0.5$
   in low-voltage systems (in medium-voltage systems above 1 kV, $k_B = 1$):
   a) With delayed tripping:
   t_k is determined from the current-time characteristic of the protection device considering the tolerance and internal time of the switching device (upper tolerance band of the tripping characteristic, Fig. 13)
   b) With instantaneous tripping:
   Low-voltage circuit-breaker (≤ 1,000 V)
   $t_k = 60$ ms
   Medium-voltage circuit-breaker (> 1 up to 40.5 kV)
   $t_k = 100$ ms
   c) In the current-limiting area of fuses:
   $t_k = 10$ ms
2. The arc power P_{arc} is calculated by means of the normalized arc power k_p and the short-circuit power S''_k:
   $P_{arc} = k_p \cdot S''_k = k_p \cdot \sqrt{3} \cdot U_n \cdot I''_{k3,max}$
   For this, the maximum prospective three-phase short-circuit current $I''_{k3,max}$ is assumed [1)].
   The normalized arc power k_p is defined in [6] as the relation between the arc power and the short-circuit power of the electrical network at the fault location, and it is mainly determined by the rated line voltage, the distance d between the electrodes, and the ratio between resistance and reactance (R/X). Guide values from [6] can be found in Fig. 13.
   If the electrode distance d is unknown, the following can be assumed for the worst case:
   $k_p = k_{P,max} = 0.29 \cdot (R/X)^{-0.17}$
3. For adaptation to the working conditions, the switchgear/switchboard type and the typical working distance must also be taken into account, which results in the following for the environment-dependent, effectively active arc energy $W_{arc,eff}$:
   $W_{arc,eff} = [(300 \text{ mm} / a)^2 / k_T] \cdot W_{arc}$
   with
   k_T → Transmission factor for the switchgear type (for guide values, see Fig. 13)
   a → Working distance (for typical values [6], see Fig. 13)
4. To select the suitable protective measures for live working, the determined arc energy $W_{arc,eff}$ is compared to the values $W_{arc,PPE}$ from IEEE 1548 and IEC 61482-1-2, as shown in Fig. 13.

1) This requires the determination of all three-pole terminal short-circuit currents, taking into account all possible network switching states, shares of motorized feedbacks, parallel operation of energy sources, etc. (in analogy to IEC 60909-0: Calculation of currents in three-phase AC systems)

Arc energy W_{arc}

$$W_{arc} = P_{arc} \cdot t_{arc}$$

Arc power P_{arc}

$$P_{arc} = k_P \cdot S''_k$$

Normalized arc power k_P

Worst case k_{Pmax}

$k_{Pmax} = 0.29 \cdot (R/X)^{-0.17}$

Guide values [6] for k_P

U_n	d	R/X	k_P
400 V	30 mm	0.2	**0.229**
		0.5	**0.215**
		1.0	**0.199**
		≥ 2.0	**0.181**
	45 mm	0.2	**0.289**
		0.5	**0.263**
		1.0	**0.240**
		≥ 2.0	**0.222**
	60 mm	0.2	**0.338**
		0.5	**0.299**
		1.0	**0.270**
		≥ 2.0	**0.253**
10 ... 20 kV	120 ... 240 mm	0.1	**0.04 ... 0.08**

with
U_n: Rated line voltage
d: Electrode distance
R/X: Ratio between resistance and reactance

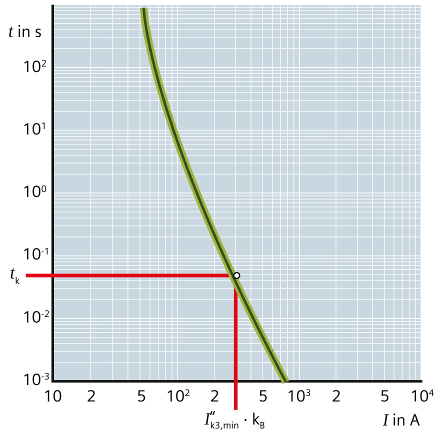
Short-circuit power S''_k

$$S''_k = \sqrt{3} \cdot U_n \cdot I''_{k3,max}$$

with
U_n: Rated line voltage
$I''_{k3,max}$: Maximum, 3-phase initial short-circuit current

Arc duration t_{arc}

$$t_{arc} = t_k = f(I_{arc,min})$$



with
t_k: Short-circuit duration
$f(I_{arc,min})$: Characteristic of the overcurrent release as a function of the minimum arc current $I_{arc,min}$ with
$I_{arc,min} = I''_{k3,min} \cdot k_B$
- Minimum 3-ph. initial short-circuit current $I''_{k3,min}$
- Current limiting factor k_B:
  Low voltage: $k_B = 0.5$
  Medium voltage: $k_B = 1$

Adjustment of box test to working conditions: Arc energy, depending on the environment $W_{arc,eff}$

$$W_{arc,eff} = [(300\text{ mm} / a)^2 / k_T] \cdot W_{arc}$$

Guide values [6] for working distance a

Type of installation	a
Low-voltage distribution boards, house connection boxes, Motor Control Centers	**300 ... 450 mm**
Low-voltage switchboards	**300 ... 600 mm**
> 1 kV	**a_{min}** 1)

1) Determination of a minimum distance required

Guide values [6] for transmission factor k_T

Design of installation	k_T
(Very) Small installations with side, rear, and partition walls	**1**
Large installations, room limitation primarily by rear wall	**1.5 ... 1.9**
Open types without important limitations of the electrode chamber	**2.4**

Comparison: $W_{arc,eff}$ with $W_{arc,PPE}$

$W_{arc,eff} < 50$ kJ	50 kJ ≤ $W_{arc,eff} < 168$ kJ	168 kJ ≤ $W_{arc,eff} < 320$ kJ	$W_{arc,eff} \geq 320$ kJ
Skin burns can be excluded; no PPE required	PPE of protection class 1 acc. to IEC 61482-1-2 required	PPE of protection class 2 acc. to IEC 61482-1-2 required	Additional protective measures required or isolation of the switchgear

Fig. 13: **Process diagram to determine suitable protective measures for live working [6]**

Standards

Medium and high voltage:

- IEC 61936-1 (DIN EN 61936-1; VDE 0101-1): Power installations exceeding 1 kV AC – Part 1: Common rules (Remark: This standard is not valid for factory-assembled, type-tested switchgear, and not for the requirements for live working)
- IEC 62271-200 (DIN EN 62271-200; VDE 0671-200): High-voltage switchgear and controlgear – Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV

Low voltage:

- IEC 60364 series (DIN EN 60364, VDE 0100): Low-voltage electrical installations
- IEC/TR 61641 (DIN EN 61439-2 Supplement1; VDE 0660-600-2 Supplement 1): Low-voltage switchgear and controlgear assemblies – Part 1: Enclosed low-voltage switchgear and controlgear assemblies - Guide for testing under conditions of arcing due to internal faults

Three-phase AC systems:

- IEC 60909-0 (DIN EN 60909-0; VDE 0102): Short-circuit currents in three-phase AC systems - Part 0: Calculation of currents

Live working

- IEC 61482-1-1 (DIN EN 61482-1-1; VDE 0682-306-1-1): Live working – Protective clothing against the thermal hazards of an electric arc – Part 1-1: Test methods – Method 1: Determination of the arc rating (ELIM, ATPV and/or EBT) of clothing materials and of protective clothing using an open arc
- IEC 61482-1-2 (DIN EN 61482-1-2; VDE 0682-306-1-2): Live working – Protective clothing against the thermal hazards of an electric arc – Part 1-2: Test methods – Method 2: Determination of arc protection class of material and clothing by using a constrained and directed arc (box test)
- IEEE 1584: IEEE Guide for Performing Arc-Flash Hazard Calculations

Bibliography

- [1] Schau, H.; Haase, J.:
  Wirkungen von Störlichtbögen bei Fehlern in Niederspannungsanlagen; VDE Fachtagung „Arbeiten unter Spannung“, 9./10. Okt. 2003, Dresden, Tagungsband
- [2] Pigler, F.:
  Druckbeanspruchung der Schaltanlagenräume durch Störlichtbögen; Energiewirtschaftliche Tagesfragen, 1976, 26. Jg. Heft 3
- [3] Glanz,C; Bergische Universität Wuppertal, Fachbereich Maschinenbau/Werkstofftechnik:
  Die Risikoanalyse mittels Konsequenz und Eintrittswahrscheinlichkeit – Methodik am Beispiel des Druckbehälterversagens im Erdgasfahrzeug; 2012
- [4] ISSA International Social Security Association, Section for Electricity:
  Guideline for the selection of personal protective equipment when exposed to the thermal effects of an electric arc fault, 2011, Edition 2
- [5] Stoll, A. M.; Chianta, M. A.:
  Method and rating system for evaluation of thermal protection, 1969, Aerospace Medicine Band 40 (1969) 11
- [6] Deutsche Gesetzliche Unfallversicherung e.V. (DGUV):
  Thermische Gefährdung durch Störlichtbögen – Hilfe bei der Auswahl der persönlichen Schutzausrüstung; 2020, DGUV Information 203-077

Annex

DGUV Information 203-077, 2020:
DGUV_203-077_de.pdf
(only available in German)

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