KAN Kommission Arbeitsschutz und Normung

Measures for reducing electric shock hazards on low-voltage systems - an analysis

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Based upon a report
of the KAN working group “Residual-current protective devices”

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1.1 Introduction

Electric current is a safe form of energy, provided it is treated responsibly. It nevertheless continues to cause fatal accidents, almost all of which could be avoided. In fact, a slight relative increase in the number of electrical accidents has been reported in the recent past, i.e. the number of electrical accidents has not decreased in proportion to the decrease in occupational accidents generally.

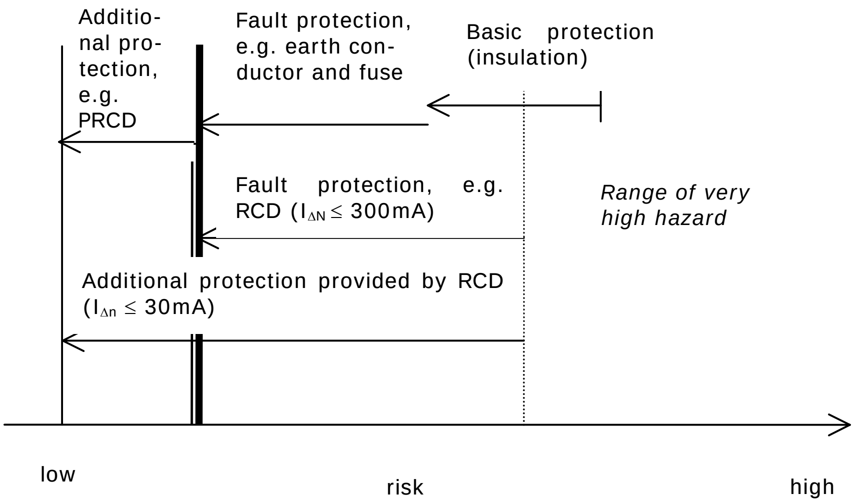
Accidents frequently involve the use of electrical appliances and tools, and work – generally unauthorized – on the electrical equipment of machinery and on the fixed electrical installation.

Hazards are greater in certain areas, for example the wet areas of the metalworking industry, and on very small construction sites. Hazards can also be caused by the use of core drilling machines and manually guided wet and dry grinding machines, and by electrical appliances employed in the agricultural sector. Electrical accidents also occur in private homes, in particular in bathrooms, outdoors (in gardens) and in kitchens.

Hazards can be reduced by protective measures, as shown in the **diagram**. This perception is based upon the presumption however that *the system has been installed completely free of faults*, i.e. in accordance with the relevant legislation and standards. The diagram shows how the risk may generally be reduced by additional protection; it should not be regarded as encompassing all situations arising in practice and describes the following principles:

- In the first instance, **basic protection**, generally some form of insulation, prevents direct contact with current-carrying parts. Should the basic protection fail (first fault), **fault protection** limits an electric shock hazard. Residual-current protective devices ($I_{\Delta n} \leq 30$ mA) provide **additional protection** in the event of direct contact with live parts should both the basic protection and fault protection fail.
- The residual-current protective devices employed for fault protection ($I_{\Delta n} \leq 300$ mA) can also cover a considerable part of the risk originally reduced by the basic protection should the latter fail.
- Residual-current protective devices employed for additional protection ($I_{\Delta n} \leq 30$ mA) can also cover a considerable part of the risk originally reduced by the basic and fault protection should the latter fail.

Diagram:



RCD: residual-current protective device

PRCD: portable residual-current protective device

1.2 Different types of fault protection

The protective measure described in the diagram entitled "Fault Protection" can be implemented in a number of ways in order to reduce the electric shock hazard associated with the use of electrical appliances.

Safety Class I appliances

On Class I appliances, i.e. those equipped with a protective earth conductor, fault protection acts in conjunction with a device in the fixed electrical installation which disconnects the power supply in the event of a fault. In order for this fault protection facility to fulfil its function, all components in the fixed electrical installation involved in the process (earth connection, disconnecting device, etc.) must be in proper working order.

The following situations may give rise to an electric shock hazard in conjunction with the use of Safety Class I appliances:

- The earth connection is broken;
- The earth connection is live;
- Devices with the function of disconnecting the circuit in the event of a fault, such as circuit-breakers or, where fitted, residual-current devices, are defective;
- Unfavourable conditions (line lengths, loop impedances) prevent appliances from being switched off sufficiently promptly by the devices intended for this purpose;
- During certain activities, electrical circuits other than those serving the appliance in use are damaged by drilling, sawing or grinding.

Safety Class II appliances

Fault protection for Safety Class II appliances (generally also including all supply lines) is provided by supplementary insulation or enhanced basic insulation, not by disconnection. This has no safety implications for the fixed electrical installation, as a protective response to faults in the form of disconnection is not involved.

The following situations may lead to an electric shock hazard during the use of Safety class II appliances:

- Both basic and supplementary insulation are damaged;
- Both basic and supplementary insulation are bridged by moisture or dirt in the working environment or by the formation of a crust within the appliance: in this case, the insulation fails to withstand the operating conditions, even when the equipment is used properly;
- During certain activities, electrical circuits other than those serving the appliance in use are damaged by drilling, sawing or grinding.

Further types of fault protection

Safety class III appliances provide protection against faults by maintaining the operating voltage at a low level (safety extra-low voltage). Safety extra-low voltage (50 V AC or 120 V DC) is generated by safety isolating transformers.

The reliability of safety isolating transformers provides Safety Class III appliances with a high safety standard. Owing to their low power (low voltage), however, such appliances are not regarded as a realistic alternative for widespread use, and will not therefore be considered further here.

In addition, fault protection can be achieved by non-conducting locations, earth-free equipotential bonding, or electrical separation. As these solutions are suitable only for certain applications and areas, however, they will not be described here in any greater detail.

1.3 What circumstances have a bearing upon safety?

The safety of electrical installations and appliances, i.e. the avoidance of hazards, is influenced both during their manufacture and erection, and during operation and maintenance.

Manufacture and erection

The responsibility for proper erection of fixed electrical installations at workplaces in Germany lies with the employers concerned. In private premises, it is shared jointly by the electrical supply utilities and the owner of the property, in accordance with the legislation governing the general conditions for supply of electrical power (AVBEltV). The responsibility for the characteristics of electrical appliances lies, in accordance with the Low-Voltage Directive, 73/23/EEC, with the manufacturer.

Operation and maintenance

The responsibility for proper operation and maintenance of fixed electrical installations and appliances at workplaces lies with the employers concerned, in accordance with the OH&S legislation. Faults may arise here as a result of incorrect behaviour on the part of the persons carrying out work (organizational errors, such as failure to observe the test regulations, etc.).

In the private sector no statutory provisions exist which dictate how to operate and maintain their fixed installations and appliances. Faults may therefore arise through a failure to perform regular inspections, or through amateur maintenance work. Installations may cease to be in a proper condition as a result. In addition, no compulsion exists for upgrading to the state of the art, as existing private installations enjoy a certain degree of exemption from new legislation. Studies of older electrical installations in the domestic sector have shown that an improper condition is by no means the exception; rather, such installations frequently fail to comply with the provisions which were in force when they were erected.

1.4 Causes of electrical accidents on low-voltage systems

Of electrical accidents involving electrical laymen in the industrial sector, damage to or faults on electrical installations and appliances are the most frequent source of electrical accidents. Such damage includes:

- Damage to plug and socket outlets;
- Damage to supply and extension lines and to couplers;
- Defective insulation on appliances themselves.

In most accidents involving electric hand-held tools, **damage to or faults on the tools or their supply lines** were responsible for the accident. The remaining accidents occurred on tools which were not defective. This category includes **earth conductor faults and insulation faults in electric sockets, insulation or earth conductor faults in extension leads,** or **damage to live lines drilled into, sawn or ground** by the tool. A high percentage of all damage to or faults on electric hand-held tools was attributable to faults in the insulation of the mobile portion of the supply cable over its free length, at the cable entry, or at anti-kink or strain relief points. Following appliance faults, the next largest category of accidents are faults in the fixed electrical installation, particularly faulty socket outlets.

Appliance faults leading to accidents are classified as technical faults. Faults on appliances, and frequently on the fixed electrical installation, such as defective sockets, could have been detected in some cases by a simple visual inspection by the victim of the accident. **Carelessness and recklessness** on the part of accident victims therefore also represents a substantial cause of accidents. Such faults are however frequently attributable to incorrect behaviour on the part of individuals responsible for occupational health and safety, as **the requisite inspections were performed insufficiently frequently, or not at all**.

Study of the locations at which faults have occurred frequently reveals a higher incidence of **incorrectly performed repair and installation work**, particularly on plugs, portable socket outlets, tapping boxes, socket outlets, and extension cables. The work in question was performed primarily by unskilled persons. **Reversal of the phase and earth contacts** and **breakage of the earth connection** are faults particularly worth noting. Repairs and additions to existing installations, in particular to portable appliances, also represent a cause of accidents.

Comparison of electrical installations and appliances which were inspected regularly with those which were not showed the safety level of the latter to be substantially lower.

An average of two earth conductor faults were detected in each of the small businesses inspected by the institution for statutory accident insurance and prevention in the mechanical engineering and metalworking industry, which indicates the high hazard level in this particular sector.

The working group is of the view that the incidence of faults in domestic installations will increase in the future, as supply networks are increasingly being operated privately, and the private companies, who are subject to harsh competition, are also responsible for inspection of the connection arrangements. In addition, it is to be feared that the established electrical supply utilities will allocate fewer resources to the inspection of connection arrangements, owing to the continual increase in cost pressures.

2 How can existing hazards be avoided?

2.1 Principles

In the view of the working group, electrical appliances and installations may generally be classified as “low-risk”, provided equipment is properly erected and installed. A certain residual risk attributable to faults arising during operation and maintenance and to ageing processes nevertheless exists.

The safety of all electrical appliances is thus dependent upon the appliances themselves, their supply lines, and their plug and socket connections being inspected at regular intervals.

As already stated, fault protection may be provided by safety low voltage (Safety Class III) or total insulation (Safety Class II). In addition, non-conducting locations, earth-free equipotential bonding or electrical separation may be employed for a limited number of applications. In all cases where none of these measures are selected, an electric appliance must be switched off promptly by a suitable protective device in the event of a fault (Safety Class I).

The proper condition of the earth conductor connection and the efficacy of the protective measures in the upstream fixed electrical installation are of decisive importance for prompt disconnection in this context. Accordingly, it is essential that regular inspections as described above be performed on the protective earth connection and on the protective equipment within the fixed electrical installation.

2.2 Supplementary measures in the fixed electrical installation

The following supplementary measures are conceivable for reduction of the residual risk in the fixed electrical installation:

a) More consistent application of the existing requirement for inspection in the commercial sector.

b) Introduction of voluntary inspections in the domestic sector.

   Realistically speaking, organizational measures (such as inspections) would be difficult to implement as a binding regulation for the hazard situation which exists in the domestic sector.

c) Upgrading of older domestic installations to the state of the art.

   The upgrading of older domestic installations would in many case give rise to considerable cost, entailing not only the installation of new equipment and switchgear, but also, for example, the laying of new lines. A less drastic solution would be to restrict the measure to specific areas, for example bathrooms and kitchens, or to equip only the socket outlets with residual-current devices. Older installations enjoy a certain degree of exemption from new legislation, however. It is unlikely that abolition of this exemption would be accepted. It also enjoys a certain degree of constitutional priority. Retrospective changes to older building structures have rarely been required by the legislator.

d) Use of residual-current devices with $I_{\Delta N} \leq 30$ mA.

The compulsory introduction of residual-current devices ($I_{\Delta N} \leq 30$ mA) would be a solution which would reduce the residual risk appreciably. This measure would however be restricted to the erection of new installations or substantial extensions to older installations.

e) In cases where hazards are known from experience to arise from a failure to inspect residual-current devices, the use of self-monitoring devices is a possible solution.

Studies performed in the past (for example by Prof. Biegelmeier in Austria, by the Elektroberatung Bayern inspection agency, the Federal Institute for Occupational Safety and Health (BAuA), or the Berufsgenossenschaften) revealed that up to 6% of all inspected permanently installed residual-current devices no longer fulfilled their protective function. Users nevertheless remain under the illusion that they are protected.

Regularly pressing the test button would doubtless improve this situation considerably, as the fault would be detected, and the residual-current device could be replaced should it be faulty. In addition to activating the test function, pressing the test button also reconditions important functions which might otherwise fail as the device ages. The problem is one of convenience with a certain relevance to safety, as the test button is often not pressed regularly, despite the existence of regulations and recommendations.

2.3 Supplementary measures on portable appliances

Portable residual-current devices (PRCDs) may be employed to reduce the residual risk associated with the use of portable appliances on socket outlets. A PRCD is not strictly speaking a protective measure in its own right; rather, it *increases the level of protection*.

Distinction is drawn between three types of PRCD:

– **With non-switched earth pole**: in the event of a fault, only the phase and neutral poles are switched. These devices are dealt with in IEC 61540, which has now also been adopted as a European standard.

– **With switched earth pole**: in the event of a fault, the phase, neutral and earth poles are switched. These devices are dealt with in DIN VDE 0661.

– **With switched earth pole and with test function**, as required by BG Information BGI 608. These devices (often referred to as PRCD-S) also assure the function of the earth conductor, and prevent electrical connection should the earth conductor be defective.

The use of PRCDs with non-switched earth pole in accordance with IEC 61540 is considered adequate by many international committees and also by some experts in Germany, evidently because the following criteria were also applied:

- They can be used on systems with any earthing configuration (an advantage for users, manipulation is avoided);
- They can be used uniformly world-wide (advantage for the manufacturers);
- Should circuits independent of those serving the equipment in use be damaged by drilling, sawing or grinding, they also present a means, without the need for additional technology, by which the stray currents from these circuits can be conducted to earth even following tripping of the PRCD.

The working group takes the view however that this attitude is based on the incorrect assumption that protection against an additional, second fault is assured at an acceptable safety level. The risk analysis regards the installation and portable appliance as a unit in this case, and concludes, in accordance with the “single-fault theory”, that the simultaneous occurrence of faults in the installation and the appliance is extremely unlikely.

In the view of the working group, however, the risk analysis should be carried out separately for the fixed installation and the portable appliance. In this case, the probability of a permanent fault in the fixed electrical installation must be assumed to be relatively high (the first fault in the context of the “single-fault theory”). The reliability of the safety function of the protective earth/disconnecting device system is therefore uncertain. Risk analysis of mobile appliances thus reveals that under normal operating conditions, the probability of a fault occurring on the appliance in addition to a fault on the fixed electrical installation is comparable to that of a first fault. At the same time, however, it may lead to considerable hazards, comparable to those presented by a “second fault”.

Furthermore, PRCDs with non-switched earth poles would not provide satisfactory protection in systems – still in existence – in which the protective earth and neutral conductors are combined to form an PEN conductor, should the PEN conductor be broken in the event of a fault.

At the same time, where PRCDs with switched earth poles are employed, the risk analysis must take into account appliances which, as described above, present a hazard by drilling, sawing or grinding into an external circuit. In the particular fault case of contact with the extraneous voltage of another circuit, the protective earth line should be maintained and not interrupted so that – in the case of sufficiently weak leakage currents - the fault current can flow to earth along the protective earth path and the necessary release current of the circuit protection is reached.

A stipulation for certain appliances that they be used with PRCDs which a) assure the protective earth function, b) do not interrupt the earth line in the event of contact with an extraneous voltage, and c) cannot be switched on at all in the event of a protective earth fault (i.e. PRCD-S) would however meet with widespread resistance, as such appliances would not be functional in certain cases (for example on IT type systems, for which earthing is not permissible). It must also be feared that many users would accept the absence of an earth conductor were they otherwise to be unable to continue their work.

2.4 Should residual-current devices preferably be fitted in the fixed electrical installation, or to the portable appliance?

A residual-current device should be fitted as close as possible to the start of the electrical supply chain within the building.

This means that residual-current devices should *preferably* be located within the fixed electrical installation. Portable residual-current devices should be used in addition for certain mobile appliances.

2.5 Function of residual-current devices under varying frequency conditions

Historically, all electrical appliances and equipment in Germany have been developed for a market upon which 50 Hz is the only AC frequency. Regulations and the conditions for (safety) tests were limited to this frequency with regard to the ability of the equipment both to handle currents, and to protect human beings. In addition, the safety concept of "protection by disconnection" actually requires a current-free earth conductor. This, too, is feasible only if no leakage currents, caused for example by variable-frequency equipment, flow through the protective earth conductor.

This basic presumption in switchgear technology, which has historical reasons and which is still made, ignores the rapidly increasing use of current-using equipment which give rise to phenomena at frequencies other than 50 Hz. The following in particular must be noted:

1. The frequency spectrum which may conceivably occur in practice is infinitely variable.
2. The tripping characteristics of circuit-breakers and residual-current devices change at frequencies other than 50 Hz. Their protective function may be impaired as a result.
3. Currents at other frequencies have different effects upon human beings. The knowledge of such effects reflected in IEC 60479-1 is not sufficient for the present situation, as it is based upon studies of a frequency of 50 Hz. The hazard has not yet been

defined, on a scientifically exploitable basis, as a function of the duration of exposure, current level **and** frequency[1].

4. Despite a number of technical solutions (such as the “Type B” residual-current devices), many cases now encountered still await a fully satisfactory solution.

A theoretical response to this situation might involve alternatives to automatic disconnection, such as electrical separation. The ensuing expense would not be economically justifiable, however.

3 Relevant provisions relating to the use of residual-current devices

3.1 Existing provisions for residual-current devices in Germany

The standards in the DIN VDE 0100 series deal with power current systems with rated AC voltages of up to 1 kV. The sections of particular relevance to the use (regulations and recommendations) of residual-current devices are Part 410 (protection against electric shock) and various parts of the 7XX series, which contains further provisions for particular areas and types of installations.

Attention should be drawn to the requirement of accident prevention regulation BGV A2 in conjunction with DIN VDE 0100 Part 704 and BG Information BGI 608, according to which additional protection must be provided on any small building site. Certain recommendations within BGI 608 can however be met only by certain portable residual-current devices which at the present time are available only from one manufacturer.

3.2 Differences in the use of residual-current devices in selected countries within Europe

The regulations governing additional protection differ from country to country; Austria in particular, but also France and Italy have stricter statutory provisions governing the use of residual-current devices in the fixed electrical installation.

These differences must be taken into account when measures to reduce existing hazards are considered, as the objective of attaining greater safety in the use of electrical appli-

[1] In IEC 60479-2, the influence of sinusoidal alternating currents with frequencies of up to 1 kHz upon the risk of ventricular fibrillation and of up to 10 kHz upon the respective limit values for recognition and the let-go threshold current is indicated by factors referenced to 50 Hz. The figures stated are based upon a small number of experimental studies, and apply to sinusoidal alternating currents. No published values exist for mixture frequencies such as those which may arise downstream of frequency converters and which deviate from the sinusoidal.

ances must be attained for the greater part by direct influence on the product standards for the appliances concerned. The various member states cannot pursue solutions of their own, however, as this area is fully harmonized by the European Single Market.

Any measures to be implemented in European product standards governing this area will be assessed by the individual countries in consideration of the local situation regarding fixed electrical installations.

4 Proposals of the working group

4.1 New fixed electrical installations

In the view of the working group, all fixed electrical installations should be fitted with a residual-current device (e.g. with $I_{\Delta N} \leq 300$ mA), if possible on the distribution board, which does not, however, have to possess the sensitivity of additional protection; in addition, all socket outlet and light circuits should be equipped with dedicated $I_{\Delta N} \leq 30$ mA residual-current devices; such devices provide the desired additional protection, as hazardous fault currents ≥ 30 mA are disconnected promptly.

4.2 Safety Class II portable appliances

In the view of the working group, certain mains-operated Class II appliances should be equipped with portable residual-current devices ($I_{\Delta n} \leq 30$ mA) in order to increase the level of protection. These appliances include:

- Portable wet and dry grinding machines;
- Core drilling machines;
- Portable agricultural appliances;
- Portable garden appliances;
- Portable high-pressure cleaners;
- Portable cleaners;
- Portable water pumps or submersible pumps.

The PRCD employed must also protect as much of the connecting cable to the power supply as possible, i.e. it should be located as close as possible to the power supply (socket outlet).

4.3 Safety Class I portable appliances

In the view of the working group, the level of safety should be increased for all Safety Class I appliances which are hand-held during operation or which present a particular hazard owing to their design, use and usual area of application (e.g. cable reels, concrete mixers), since:

- The reliability of the protective earth conductor/disconnecting device system is critical – a major risk of plant faults exists, irrespective of the mobile appliance in question;
- Faults generally occur during operation of the appliance.

In the view of the working group, these Class I appliances should be distributed with portable residual-current devices with switched earth pole.

In all cases, the PRCD should protect as much of the connecting cable to the power supply as possible, i.e. it should be located as close as possible to the power supply (socket outlet).

The corresponding test regulations for PRCDs are to be drawn up by the committee responsible for design requirements for PRCDs (in Germany, UK 541.3).

For appliances which may come into contact with other circuits (e.g. core drilling machines, rotary hammers), OH&S regulations should, where not already in place, be issued requiring that these appliances be used only in conjunction with PRCDs with test function in accordance with BGI 608. Manufacturers should include in the respective instruction handbooks a recommendation that such PRCDs be employed.

4.4 Technical arrangements for residual-current devices in the fixed electrical installation

Experience has shown that electrical installations, appliances and residual-current devices are not inspected regularly by operators as recommended.

Should a residual-current device be defective, the user continues to assume, incorrectly, that it is fully functional, and that he is protected accordingly.

For this reason, technical solutions which obviate the need for the organizational measures formerly necessary must be developed to maturity as soon as possible, and laid down in the standards.

4.5 The need for research and development in the non-50 Hz spectrum

The existing terms of reference for switchgear technology fail to take into account the increasing use of current-using equipment which give rise to phenomena at frequencies other than 50 Hz. Research into the underlying principles concerning the effects of variable-frequency currents upon human beings must be encouraged and supported financially due not least to the increasing use of frequency converters for infinitely variable conversion of the given supply voltage and frequency into variable values. Until this is done, meaningful risk analysis is not possible.

The results of such studies must be used to review the efficacy of protective measures, and to specify design regulations for protective switchgear. The boundaries of the “frequency/current/duration of exposure” function must also be defined in order to limit the discharge currents from frequency converters. If the proven protective measures are to be implemented, this is necessary because the appliances (e.g. frequency converters) must enable protective switchgear to be employed and to operate properly.

4.6 Older domestic installations

Domestic electrical installations must also be maintained in proper working order at all times. Regular inspection by skilled electricians, as is performed in the commercial sector, would also contribute to safety in this area.

It is therefore recommended that inspections be performed by skilled personnel at regular intervals on the entire electrical system; in the case of rented property, the system of the affected living unit should also be inspected at each change of tenant. Such skilled personnel are trained in the measures which are necessary and appropriate for the rectification of faults.

The ministries, industry associations and insurance companies affected can actively use the means at their disposal to create incentives for the implementation and promotion of these measures.

5 Further literature

Institution for statutory accident insurance and prevention in the precision engineering industry, **1998** “Gefahren des elektrischen Stroms”

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