

ARC FAULT FREE DESIGN FOR ELECTRICAL ASSEMBLIES

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Abstract -

Low Voltage Motor Control Centres are designed for applications in electrical distribution grids ranging up to 100kA. Where the busbars can be designed to withstand these currents for 1s (I_{cw}), it is hard to imagine that a Motor Control Centres can survive an internal arc at these short circuit ratings.

Motor Control Centres can be designed in such a way that the consequences of such a fault are limited. Nevertheless, even with a Motor Control Centres according international standards, safety is only met on main items and equipment will suffer full damage. Consequently operating personnel might suffer as well from such an internal arc fault.

The IEC by means of TC17D has developed a technical report (IEC/TR 61641) that describes how the safety with respect to the operating personnel of an LV switchboard can be tested and assessed. This report recognizes that severe damage to the equipment may occur, as long explosion will not hurt the operating personnel as results from an internal arc.

For operating personnel and equipment it would be much better to prevent that such a fault can occur within the MCC, so-called "ARC FREE Motor Control Centres".

The Arc Free Motor Control Centres is achieved through the application of Fault Free Zones, areas where special measures have been taken to avoid the occurrence of an internal arc.

The following paper discusses a number of causes for internal arcing faults and gives solutions to prevent such faults with the purpose of creating a design of an assembly having:

Index Terms — Arc-flash phenomenon, Possible causes to internal arcing, Standards on isolation/insulation and arc testing, How to prevent internal short-circuit, independent barriers, Arc fault free assemblies, Arc Free zones, Arc fault protected motor buckets, safety incorporated in the equipment versus safety incorporated in the person

I. INTRODUCTION

All electrical assemblies according to the standards IEC 60439-1 and ANSI/NEMA, main assemblies and Motor Control Centres (MCC's) are required to withstand a short circuit current that is liable to occur. Part of the type tests that these standards require is the verification of the withstand capability of the through going short-circuit current. This short circuit current occurs for instance during an external short circuit in an outgoing feeder, which is not cleared by the outgoing short circuits

protection device SCPD. According to these standards this test is performed on the main, distribution busbars, and incoming unit, if any, that are short-circuited with a bolted link on the end. The short circuit withstand current capability test is carried out for the maximum peak and RMS value of the prospective current and duration as specified in the standards. The ANSI/Nema standard requires the short-circuit current duration to be 3 cycles, the IEC requires in general 1 s, and optional 3 s.

The assembly passes the test when it is still intact afterwards, thus suitable for further operation.

The practical relevance of this test must not be over rated. It is very unlikely that during the lifetime the main and distribution busbar system have to withstand these rated short-circuit currents. Normally the short circuit protective devices in the outgoing shall clear these through going short-circuit currents, so it is unlikely that the main and distribution bus bars systems are faced to these short circuit currents. If the busbar is subjected to these short circuit currents, it is most likely caused by an internal arcing fault.

At such an event, the assembly is subjected to very different stresses and threats for its surroundings which outcome is not defined in the IEC 60439-1.

In the 70's, internal arc fault accidents occurred in assemblies operated at petrochemical plants, one of them unfortunately with fatalities. This was the inducement to find a new approach for the development of a new design LV MCC.

In modern process industries where in general a high short-circuit capacity is present, the internal faults in the switchgear are a potential risk for operating personnel, the equipment and for the process.

National and international standardization institutes already incorporated tests for conditions under arcing in product standards for medium voltage switchgear. It became clear that with the increasing short-circuit capacity of LV distribution grids such a rule also applied to LV switchgear.

IEC sub commission 17D has developed a technical report IEC/TR 61641, for testing an assembly under conditions of arcing due to internal fault. IEEE has developed a guide, IEEE1584TM-2002, to perform calculations based on actual situations and to determine the arc flash protection boundary.

The following paper discusses a number of causes for internal arcing faults and gives solutions to prevent such faults. The purpose is to create a design of an assembly having fault free features for the incomer, the main busbars, the distribution busbars, and the arc proof motor buckets.

II. SHORT CIRCUIT THROUGH INTERNAL ARCING

The phenomenon of an arc caused by an internal fault from ignition until the interruption of the energy supply is a very rapid and destroying event. The inducement of the ignition can be caused by various errors that will be discussed later in this paper. An internal fault often starts with an unintended (short) circuit within the assembly that is blown away within milliseconds. A mixture of ionised gases developed due to vaporizing of metals takes over the current path. This metal vapour reaches high temperatures of 5000 – 10,000 degrees C. At the same time, a high pressure is built-up within the enclosure, due to the increasingly heating up of the developed gasses not able to expand within the enclosure. If the current is not interrupted through a SCPD, an explosion may be the result. The seriousness of this explosion depends on the amplitude of the fault current, the duration of the arc and on how well the enclosure is able to contain the explosion.

However, there are more dangerous effects of this phenomenon occurring. Like for example poisonous gases that are developed due to vaporizing of metals and insulation materials. These gases may have short-term and long-term effects on the person(s) inhaling them. The gasses are so hot that the clothing of persons in the vicinity of the assembly may start burning and exposed skin can suffer severe burning due to radiation of the arc. Note that severe burns are often caused by ignited clothing and not by the original arc flash or the fire. The explosion can be so loud that damage to the hearing has to be expected. Besides the direct danger of arc faults, secondary effects like those of the occurrence of dazzling are often worsened by panic movements. The number of injuries from arc flash accidents in the presence of peoples is likely very high, however reliable records do not exist.

Besides the very serious consequences for the operating personnel or technician working on or standing close to the assembly, arcing faults can lead to considerable economic losses. Production loss and long downtimes through repair works have to be taken into account.

An arc-flash in the main or distribution busbars most likely result in loss of equipment, consequently loss of supply, i.e. loss of product.

III. HOW DO INTERNAL SHORT CIRCUITS OCCUR

Internal short circuits are most likely a result of hot spots, tracking across insulation material, animals or vermin entering into the assembly, loose parts or human errors.

1) *Tracking across insulation material*

Comparative tracking index (CTI) values categorized in material groups are very relevant in this perspective. The applied insulating materials play an important role avoiding the chance of an internal fault due to deposits of dirt and dust or condensation of water vapour when ambient temperatures varies during the day.

2) *Hot spots*

A possible cause of short circuit can be a bad connection. A bad connection will cause the generation

of heat and/or coaled insulation material, which in the end likely can lead to an arcing accident.

Reasons for bad connections may be:

1. False tightening torques at connections caused by poor construction methods or by lack of maintenance;
2. Excessive vibrations or atmospheric conditions. Provisions should be taken to avoid the risk of corroded or dirty contact surfaces. All connections are preferably to be silver plated, provided with multiple contact spots and provisions for contact pressure with sufficient capacity to compensate for any shrinkage, vibration or material flow;
3. Contacts not remaining closed under short circuit conditions. If a contact opens due to the repulsion forces of the short circuit, arcing occurs on the contact spot and a copper-oxide or aluminium oxide film remains. After such occurrence, the electrical resistance of that contact or connection is likely substantially higher and more threatening, probably not stable;

3) *Whiskers*

Another cause for a short circuit in an assembly, which we found in the petrochemical industry as well as in the food industry, is whisker formation. Silver whiskers may be the cause of unexpected short-circuits. A silver whisker likes to grow on sharp edges of silver coated parts in a sulphur rich, warm and moisture environment;

4) *Animals and vermin*

Large openings in the enclosure allow small animals and insects to enter the assembly with the risk of them touching live parts and consequently introducing an unintended circuit that develops to an arcing fault;

5) *Fungus*

Moisture may cause fungus to grow within the enclosure that may flourish on the hotter spots, i.e. connection points.

6) *Human error*

Wrongly operated switchgear and carelessness during maintenance works and cleaning the equipment. These may introduce errors with destructive faults leading to internal arcing. Notorious are the accidents caused through a forgotten tool or loose laying bolts and nuts in the assembly. Note that loose ferro metallic objects may move under de influence of magnetic fields caused by inrush currents.

IV. DEFINITIONS

Arcing fault:

An arcing fault is the flow of current through the ionised gases between conductive parts with electrical potential difference. The arc becomes visible because of the flash of the ionised gases.

Internal arcing:

Arcing inside an electrical assembly between phases, or phases and neutral, or phases and earth (ground), or in combination.

Arc fault free zone (in an electrical assembly):

Part of an electrical assembly where the insulation between phases, phases to neutral and to earth, consists of two independent effective barriers, both air and solid insulation material.

Arc proof (part of an electrical assembly):

Functional part of an electrical assembly that contains SCPD that will limit the effect of an internal fault. This SCPD is selected to confine the effect of an internal arc within the compartment and to prevent adjacent compartments to be affected in its availability.

V. HOW TO PREVENT INTERNAL ARCING

For the prevention of the occurrence of an internal fault, a high level of protection is required, similar to extra provisions on equipment designed for (potential) explosive atmospheres. Safe operation shall not be impaired under the condition when one protective measure fails. This implies that in this case protection or functionality shall remain effective. The constructional provisions to achieve this safety level are required to be designed independently to each other. This means that a failure of one protective measure does not impair the other.

Simultaneous failure of the two independent provisions is deemed unlikely and does not need to be taken into consideration. Over 20 years of practical experience with Arc Free, design philosophy has demonstrated its value.

According to the applicable International Electrical standard for Low-voltage switchgear and controlgear assemblies, the IEC 60439-1, "Type Tested Assemblies (TTA) and Partially Type Tested Assemblies (PTTA)", assemblies are not required to be designed to take failure of single protective measures into account.

This means that a spacing and a solid insulation barrier may be designed in such a way that just one single failure, such as bridging of that spacing or creepage of that insulation, e.g. bus bar support, can result in a short circuit.

In case of electrical installations with high short circuit capacity and long clearing times of the SCPD's, the consequences of an arc fault are serious and even likely to cause human injury to someone in the vicinity of the assembly. Engineers responsible for specifying low-voltage switchgear must carefully consider whether applying only the IEC 60439-1 requirements offers sufficient safety.

Note that for high voltage assemblies' according to IEC62271-200 testing under conditions of arcing due to internal fault is normative.

VI. HOW TO QUANTIFY THE RISK OF AN INTERNAL ARCING FAULT

While every assembly has a certain risk of failure through an internal fault, there is a need to quantify this risk. Primarily assessed is the possible level of injury that can be caused to operating personnel.

In the IEC world there is a Technical Report on Internal Arcing testing, the IEC/TR 61641.

The ANSI/NEMA in the USA has an IEEE guide on arc-flash hazard analysis. Both intend to quantify the internal effects of an arcing fault within a specific assembly on persons operating or standing close to the assembly.

However the negative effects of several parameters are not taken into account, e.g. the poisonous gasses and noise.

Note that the recommendations of IEC 61641 are not accepted in the USA.

The IEC/TR 61641 is a guide for testing assemblies designed according to IEC 60439-1 under internal arcing conditions. This technical report suggests that the actual tests are an agreement between the user and the manufacturer of the assembly. The test described in the technical report is the most onerous for the assembly but it can be executed in a different manner if the user wishes to. The technical report suggests 5 criterions to assess the safety for operating personnel.

In the assessment of IEC/TR 61641 the availability and operational state of the assembly after the test is not included. To the user, of course, primarily there is the interest for personal safety, but the availability of the switchgear is also important. Absence of the availability most likely causes loss of production for a plant.

The IEEE1584TM -2002 is a guide to perform energy burst calculations based on actual situations and to determine the arc flash protection boundary. The outcome of the calculation is a measure for personal protective equipment (PPE) and the distance a person shall maintain to the assembly. The IEEE1584TM ignores the fact of a person being startled by the exposure to an arcing fault explosion. This exposure may cause temporarily or long term insecurity in his work or even permanent fear of operating electrical equipment.

Note 1. The IEEE1584TM is not used nor recognized in the IEC world.

Note 2. In the perspective of the above, IEEE1584TM is only of value for existing switchgear.

VII. DESIGN OF AN ARC FREE ASSEMBLY

The following describes the concept for an assembly in which the main distribution system is provided with fault-free zones. This is achieved through the application for two independent isolation barriers between phases, phases and neutral, and to ground throughout the assembly and arc-proof outgoing units.

The design of the bucket offers protection against electric shock under all operating conditions, installation work, and maintenance. Moreover, any fault liable to occur during either maintenance and / or operation shall be confined within the enclosure of the bucket without any external effect.

A. General:

All functional units such as terminations for external conductors, protective devices including the auxiliary equipment of each individual circuit and the bus-bar system are placed in separate compartments. The form of separation is at least 4A.

The partitioning between live parts in adjacent compartments complies with at least IP XXB for all conditions of use: doors open and buckets either in-position, buckets removed or during racking of buckets. (Test fingers cannot touch live parts).

With all doors closed, the degree of protection of the

enclosure should comply at least with IP 41 (straight round wires or other straight objects with a diameter of 1 mm or more and dripping water cannot enter the enclosure).

The above requirements ensure safe working with reference to the risk of contact of live parts.

B. Design of the incoming feeder:

The incoming feeder of the assembly is either provided with an Air Circuit breaker (ACB) or Moulded Case Circuit breaker (MCCB) suitable for the maximum short-circuit current to be expected or with a switch disconnecter able to make - and break all currents including any overload. Such switch disconnecter is acceptable if the required over current and short circuit protection, down to the protective devices of the out-going circuits, is effectively covered by the protective device on the supply side. This may be in a distribution circuit from another LV board supplying the board, or from the medium voltage CB of the supply transformer.

Within the supply, section itself additional isolation barriers are provided between the supply phases on both sides of the breaker.

Termination of the incoming cables is done with blocks that only accept straight connected cable rather than cable lugs that enable the cables to leave under an angle with the potential risk of touching the adjacent one.

C. Design of the bus-bar systems:

Generally, a (main) switchboard or MCC has two busbar systems.

The main busbar system, often a horizontally placed four (4) -conductor busbar that distributes the electrical energy to the distribution panels placed side by side. The other busbar system is the distribution busbar that is in each distribution panel where it supplies one or more feeders fixed or withdrawable.

1) The main bus bar system:

To achieve the two independent and equally functional barriers, the fault free concept provides the required clearances between busbars of different phases and between busbars and frame and each separate bar is insulated with an epoxy over its full length.



Fig. 1

The clearances and creepage distances are designed and tested for 1,000 V and in compliance with at least the basic requirements applicable for the assembly. The epoxy coating is able to withstand at the minimum 1,000 V when wrapped with aluminium foil.

Note: The current carrying capacity for busbars covered with insulating material proved to be better than for uncovered ones due to the fact that the heat transfer by radiation is much better.

Joints for the extension of individual copper bars and connection to the distribution bars (droppers) are also a potential risk to be the source of an arcing fault. While most users plan their maintenance with large intervals, the design of these joints requires much consideration. In the fault free concept, the joints have been designed to be maintenance free. Through the application of the best copper quality, suitable steel bolts and lock washers, the joints provide good contact and steady contact pressure that compensates for any material thermal grow and shrinkage throughout its operational life. Furthermore, all connections are encapsulated by solid insulation material.

2) Distribution busbars:

The distribution busbars per phase consists of two silver plated copper bars with a spacing of 20 mm. This applies to both phases and neutral if applicable. The bus-bar cross-section depends on the required load current. The clearances and creepage distances across the supports of the phase bars comply with the requirements for 1,000 V. In addition, each phase and neutral, if any, are individually encapsulated with a glass-fiber polyester duct over its full length.

The Arc Free design of the draw in contacts to the buckets is realized with completely shrouded with solid insulation stub contacts. The design of the stub contacts is such that any possibility for a short circuit on the supply side is excluded. Even during insertion of the bucket, the supply stub contacts are firstly completely insulated before electrical contact is established with the distribution bus bar.



Fig. 2

D. Design of arc-proof motor starter buckets:

While motor starter units are the most operated parts of the equipment, they are a vulnerable part of the equipment. Therefore, during the design stage special focus has been conducted on safety during operation. Human errors through operation and maintenance are a major root cause to internal fault in the bucket.

Motor starter buckets are equipped with the required protective and auxiliary equipment. To guarantee safe operation and maintenance the following positive driven mechanical interlocks are provided:

- Racking in the bucket, a mechanical interlock prevents insertion of the bucket while the isolator is not in the open position;
- A door interlock prevents opening of the door while the isolator is in the closed position;

When the bucket compartment door is opened and the bucket is still racked in, the switch disconnect is in the open position, therefore it is not possible for operating personnel to reach live parts.

Due to the constructional limitations, variations in components and the complexity of the electrical circuits, it is difficult or in general even by the application of a second barrier to exclude all possible sources for an arcing fault within such a motor starter bucket. For this reason, motor starter buckets in general cannot be completely designed fault free.

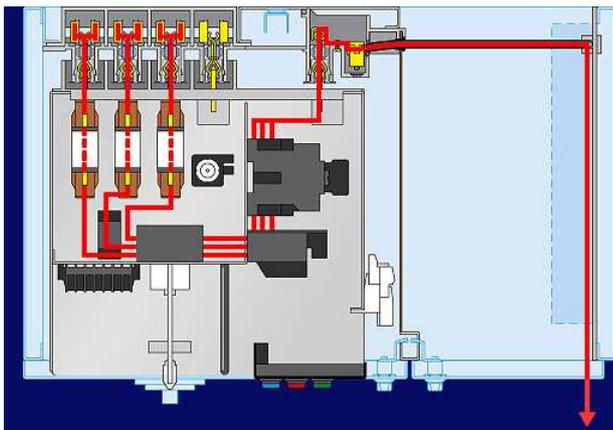


Fig. 3

In the arc free concept for the motor starter bucket is chosen for a combination of an arc fault free zone and an arc proof compartment.

A weak part in many designs is the stub contacts of the starter bucket.

A special contact arrangement is developed in order to guarantee long-term high quality contacts and to eliminate possible arcing faults in case of racking motor-starters bucket. This contact has two design features, a mechanical improvement of the contact pressure and an "electrical" improvement of the contact pressure.

Through-going short-circuit currents increase the contact forces on both the pin of the bucket and on the vertical bus bars. Consequently preventing contact repulsion under short-circuit conditions.

The draw in contacts on the rear of the bucket that connect to the scissor contacts to the distribution busbar are fully insulated when racked in. While racking in the

bucket firstly the electrical connections to make are fully isolated with insulating barriers so it is virtually impossible that an internal fault can develop in that area. To create a fault free zone in the bucket up to the supply side of the SCPD, the fuses are mounted directly on the incoming stub contacts and the connection to the MCCB are completely insulated with solid insulation.

In addition, re-striking has to be prevented. For interruption of the arc, the protective device generates an over voltage in the case of an arc. This over voltage appears on the supply side of the breaker and this over voltage can easily be as high as 1500V and therefore a potential risk for a re-strike at the supply side of an MCCB when not sufficiently isolated. Such an event would be dramatic and must be prevented under all circumstances. (see construction detail on the rear side of the bucket).

To create an arc proof compartment, the rating of the SCPD is selected by taking into account the required short-circuit protection of the out-going cables and the control gear of the circuit (contactor / relays). In addition to that, in the event of any arcing fault within the bucket, damage is confined within that bucket.

The maximum arc fault current to withstand depends on the required short-circuit withstand current and the rated voltage of the assembly.

For determination of the required minimum arcing fault current, measurements in the laboratory proved that 0,5 times the calculated 3-phase bolted short circuit current is a good practice value. The SCPD of the bucket has to operate under these conditions within 0,1 second. If fuses are applied the rated maximum shall be 400 A, this implies that the available bolted short-circuit current shall be at least 12 kA and for fuses rated 250 A, the short-circuit current shall be at least 5,5 kA.

The above minimum prospective short-circuit currents are in general available in MCC's for the process industry.

For MCCB's the setting, operating characteristics and current limiting features have to be taken into consideration and it may be needed that additional tests have to be performed.

E. Design of the cable compartment

The out-going cables are terminated on a terminal block provided with identical stub contacts as for the bus-bar connection. Safe working on the terminals - protection against contact with live parts as well as the risk of initiating an arc-flash - is guaranteed under all circumstances. The terminals can only be reached when the bucket is removed from the assembly.

VIII. SAFETY DURING OPERATION

Subject to be discussed is: Safety incorporated in the equipment *versus* safety incorporated on the person

In the IEC countries, the majority of the Petroleum and Chemical Industry utilizes arc fault resistant or arc free panels, while in the ANSI/NEMA countries these industries mostly rely on arc flash Personal Protection Equipment (PPE). However, also in the ANSI/NEMA world the situation is changing, where 'safety at personnel' to 'safety at installation' is considered as well.

Choosing for safety incorporated in the equipment ["intrinsically safe equipment"] makes one independent of the operating discipline. The human factor is in most cases the weakest link in the safety chain...

Utilizing Arc fault resistant panels is not only a matter of the kilo-amps, but also of the fault clearing time! The concept only works when the panels are operated within their specification and when all doors and covers are closed.

This means in practice that a protection survey will be part of the risk assessment on the installation.

In the Netherlands, this risk assessment is mandatory by rules of Labour Inspection: employers are responsible for the safety of their employees.

Experience learned that the situation was in practice below expectation: especially on older installations, the damage curve was sometimes violated, which makes the equipment not properly protecting the employees.

A good method for safe operating is to limit the short circuit energy to an MCC board. Good practice that is based on many decades of working experience is to protect the MCC's with fuses or equally fast acting circuit breakers, having a maximum current rating of 630 A.

In the ANSI / NEMA / NFPA world, Arc Flash Hazard Distance (AFHD) is a known metric in relation to arc flash hazards. This AFHD describes a sphere with a distinct radius around the point where the arc flash occurs. Within the sphere is the hazard zone.

It is relatively new within the IEC / EN world to consider flash hazard distance, although it is upcoming. At the moment in the IEC / EN world only shock hazard distance is mentioned.

This AFHD is only of value in non-Arc Flash resistant installations, e.g. in open(ed) installations. When working within the AFHD, addition PPE will be required.

The type of PPE depends on the energy being developed at the fault place, and the distance.

Use of extra PPE has several disadvantages: there is a possibility that they are not used, or the wrong type is used, and they are often inconvenient to wear. Also, mention the costs involved for buying and maintaining this PPE.

Therefore a proven philosophy is: racking and switching only with closed doors or equivalent construction [e.g. arc-free], because the most critical phase is racking and switching draw-out units, for example due to possible loose parts, tools left behind or misalignment.

IX. CONCLUSIONS

International standards do not incorporate sufficiently requirements to prevent the internal fault and limit the effects.

Although arc fault testing according to IEC/TR 61641 or calculation according to IEEE 1584TM may guarantee a certain degree of safety for operating personnel, it does not increase the availability of the assembly.

Prevention of an arc-flash is a far better measure than limiting the effects. Design of arc-free or arc-flash protected switchgear and MCC's is possible.

The design of Arc Free Switchgear is an integral part of

the philosophy of safety and operation

More than 20 years of practical experience has demonstrated that the application of two lines of defence against internal arcing faults provides a reliable and safe design of the incomer and main distribution sections. The motor starter buckets can be designed to guarantee safe working under all conditions and able to withstand any internal arcing fault, without any external effect for the electrician or operating personnel.

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