

SAFETY ANALYSIS OF A MV ELECTRICAL INSTALLATION, REGARDING ARCING FAULT RISK

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ABSTRACT

Arcing faults are a great concern in any electrical installation. However, and despite all precautions, the probability of occurrence can't be equal to zero. The paper discusses situations, effects and how mitigation of these effects can be sought through design choices during the design stage of the installation. Arc-proof switchgear is contributive, but can't address all the situations, nor cover the whole range of possible fault currents.

INTRODUCTION

The main purpose of this communication is to suggest unusual ways to look at a very serious topic. The reader should recognise that some statements could be sharp, but perhaps not completely wrong, and that it could sometimes be wise to have a broader approach of the safety than only technical specification of equipment. Otherwise, some dead-ends could limit the evolution of the industry, and even compromise the very basic goal of the designers.

Seen from manufacturer's side, they sometimes work with a high level of business risk, due to the fact they invest time and money to provide (expensive) technical solutions the need of which could be cancelled by using a different approach of safety. Therefore, we, Schneider, are interested in sharing these views and concerns with the users, as we think we could, both manufacturers and users, take advantage of a well balanced risk management.

GENERAL

Market trends

The safety record of electrical equipment is very good, as the already existing standards and state of the art provide a very low failure rate of electrical installation. Nevertheless, the introduction of new technologies, the increase of the ratings as well as the increase of the usage factor (less operational margin) raise questions about the future. Then, some pressure does exist for "increased safety". Due to the very small number of events, statistics can't be relevant to assess correctly the balance to be made between cost and expected results and, therefore, the behaviour can be much irrational.

Consideration should be given also to the conflicting requirements which are sometimes expressed, as the wish for reduced dimensions together with easy maintenance and upgraded ratings for instance. When such conflicting requirements are stated by different functions in the user's

organisation, each off them having its own goals as "safety", "financial", "operation", it shows a lack of knowledge-sharing which could prevent any real optimisation. The growing usage of sub-contractors makes such sharing more and more difficult, due to the increased number of "contracted" boarders, with associated costs and liabilities.

Available performances

The currently available ranges of MV switchboards are, for some of them, validated up to short-circuit current of 50kA. It becomes really a technical issue to be able to manage the amount of energy which is dissipated by such a powerful arcing fault. Beyond a dedicated design, with reinforced structures, identified gas flow paths and sometimes doubled metal sheets, more and more solutions rely also on the use of either the cable ducts or a gas exhaust duct to funnel hot gases far from operator's possible location. By introducing such features, the interaction between the switchboard itself and its installation conditions is highlighted. But it is not a new situation.

It means also that the expected performance is only achieved when all the functions, as stiffness, tightness, venting and so on, which participate are actually in working conditions. Typically, a reinforced door is useless if the switchboard is operated door open... All the various conditions which could occur during maintenance work, or sometimes during operation, are clearly not covered by the tests. This is partly due to the high number of varying parameters which makes the definition of the test conditions unrealistic, or at least always unsatisfactory. It has to be acknowledged also that the demonstrated performances are the upper limit of the fault severity the switchboard is designed to withstand, and that any increase in the severity – and the hypothesis of an open door is obviously a constraint - with other parameters unchanged could lead to failure. So the demonstration provided by type tests has to be considered as rather conventional, never fitting perfectly the actual operation conditions, but intended to provide the basis for comparison on one hand, and for confidence on the other hand. The limitations of such demonstration are known and clear.

Physical and technological limits

Magnitude of phase to phase faults reaches usually now several tens of kilo-amperes. With arcing voltages roughly

between hundred and two hundreds volts, the power dissipated at the fault location could be for instance $40 \times 10^3 \times 150 \times 3 = 18 \text{ MW}$. The heating and burning effects of such a power level are tremendous, and shall be somehow mastered in order to get a reliable (meaning repeatable) behaviour. One of the current trends of the market is the request for more compact installations, which makes mastering arcing faults even more difficult as pressure can build up very fast within limited space.

The definition of the acceptable behaviour is one of the first questions to be considered; the assumptions made when using the IEC type test is that people in the vicinity of the equipment shall not be burned, which means that thermal effects shall be contained for one part, and driven away for the other.

Many other criteria could be considered as relevant, depending upon the installation and operation conditions, and upon the goals which are targeted. But the physics itself introduces boundaries which can't be over passed. These limits somehow challenge the design of powerful installations and should lead to consider the safety issue in its whole.

However, the limited experience of field faults seems also to show that the actual short-circuit power, at the instant of the fault, is much often far below the specification value of the installation, and that participates significantly to the rather good behaviour. That means also there is a general over-specification and accumulation of safety factors which could lead to extra expenses, or even to dead-ends (no technical solution to fulfil all the required performances).

SAFETY AND RISK ASSESSMENT

Goals

Safety for people

Personal safety is one of the first goals which come to mind when considering arcing faults. Personal safety is nevertheless only at stakes if someone is likely to be in the vicinity of the fault when it occurs. This obvious statement has to be cautiously considered when weighing design and operation choices of an installation.

It is common statement in so-called western civilisations to say "life has no price", but accidents do have a cost for organisations, apart from the social aspect. Therefore, the choices of solutions, including their contributing features to personal safety, have to be made according to objective criteria, as far as relationship to health and life can be unbiased.

Protection for installation

Considering "protection" when the fault is already there means that protection applies to something else than the faulty equipment. A switchboard is not "protected" against its own internal faults, but parts of installation can be protected against the effects of arcing faults in other part or equipment.

One has to identify clearly what is the goal of such

protection, and the required level to ensure that the goal is reached. Let's take an example: if after an arcing fault, an electrical room is heavily polluted by conductive dust, equipment in the room, even not directly damaged by the fault, is not available for immediate operation. In such situation, a goal expressed as "no damage on surrounding equipment, no replacement needed" is perhaps reached while a criterion expressed as "minimal down-time on the substation" is not satisfied. If the cleaning up is as long and as expensive as the replacement of the polluted equipment, there is no advantage to protect him from direct damage. That means there are some step effects in the protection scale; if the goal is not fully reached, it is not worth trying to reach it.

If your down-time cost is expressed in M€per day, saving the price of the surrounding equipment is probably not the first criterion if such equipment is available "on the shelves". Capability for repair, or for emergency temporary operation, of the installation is much more important when the lead time for heavy equipment is expressed as several weeks or months.

Interest in "protection for installation" can be measured on several scales, according to the main focus of the process.

Efficiency of operation

Most of end-users are motivated by their process, and consider electricity as a utility among others. And basically utilities are considered to be available to keep the process running. Therefore, a very strong criterion is the availability, or the un-availability which could be expressed either in terms of number of outages, or duration of outages, or most often both.

Number of outages, or probability of occurrence of outage, can be addressed through:

- care taken to prevent triggering events (overvoltage limitation, load management, proper maintenance...)
- design of an effective protection plan, incorporating clean grading between breakers
- dual-feeding at various levels in the installation, with automatic transfer devices

Duration of outages can be influenced mainly by two criteria:

- the possibility for emergency operation of the installation (through looping capabilities, alternative power supplies...). Range is from minutes to hours.
- the repair or replacement time of the damaged part of the installation (extend of the damages, availability of spare equipment...). Range is from hours to months...

On both these criteria, it seems clear that preventive actions could be made during the design stage, and the reward is huge.

Methodology

Failure mode analysis

Failure mode analysis is used extensively during design process of the products, and not only the electronic ones. Performing an extensive review of the possible "initial" failures on components or basic functions, as well as

possible miss-operations by users, the analysis aims to identification of the initial conditions as well as the possible developments and consequences within the equipment and outside of it. If such consequences are unacceptable, the design has to be improved either to prevent the initial failure, or to drive the consequences towards another result. It provides a loop process which enhances greatly the confidence level a user can have.

When considering an installation, a similar analysis can be made and, of course, the depth of this analysis has to be kept relevant. The initial event could be considered as, for instance, the failure-to-trip of a protective relay but without looking for the possible internal causes of such failure - that would be the scope of FMEA (Failure Mode and Effects Analysis) of the relay itself -. External influences have to be considered in any case. For switchgear, a dielectric breakdown in a GIS is typically due to a product or an overvoltage problem while for an AIS switchgear, the origin could be also found in poor maintenance or harsh service conditions. That means such external influences have to be listed as possible initial events in the analysis.

Probabilities

Probability of an event could be either expressed in terms of event per period, e.g. 10^{-6} per year, or in terms of event per occurrence or solicitation, e.g. 10^{-4} per tripping operation. A dielectric breakdown on lightning impulse overvoltage has a probability "per solicitation" - typically less than 2/15 at the rated level for a self-restoring insulation -, but if the occurrence of lightning has a rate per period, the resulting failure rate of the equipment can be expressed also per period. If the keraunic level of the area is such that the network is submitted to 100 impulses per year reaching the insulation level of the equipment, the resulting failure rate could be as high than 12 per year ! For an overhead line ceramic insulator, it could be acceptable, but for any indoor equipment it is not, hence the importance of mastering overvoltages...

Considering safety, the probability of injury generated by an arcing fault is to be considered with the probability of fault itself, biased by the probability of presence of personal at the instant of the fault. For an unattended installation, this later probability is very low when considering random failures. When looking to possible operation failure, the situation is much different, and the probability to have an operator in front of the switchgear is equal to one in case of fault during manual closing operation for instance. This probability is reduced to zero if the operation is made remotely. Therefore, the operating procedures have a huge impact on the overall human safety aspects.

Ranking in failure mode

The idea of rank for a failure could be summed up as "the number of abnormal conditions and events which occur simultaneously to generate the failure". Analysis of catastrophic failures generally shows that several faulty or abnormal states were already established when the triggering event happened.

As an example, a fault on a cable can be a first order fault

(either ageing or accident), but if at the time of this fault the protection relay is unavailable for any reason, then the failure becomes a second order one, the consequences of which are generally worse. This example highlights the advantage of the watchdog feature in digital relays compared with the scheduled check of mechanical or analogue ones: the duration of the unavailability is much reduced by the alarm, and then the probability of a second order failure is drastically reduced. The same applies to any on-line diagnostic function, as such functions reduce the probability of keeping a faulty situation unknown until it is revealed by a triggering event.

Mapping and weighing of the risks

Criteria to be used

Several criteria, and related scales, can be used to assess the risks of an electrical installation. Every single event considered during FMEA can be positioned according to these criteria. The relevancy of each criterion has to be determined on a case by case basis, according to the installation itself, to the process it powers, to the human environment and so on. As examples, one can consider:

- down time of the process (from zero to months, lead time for spares, work time)
- direct cost of the repair (damage to building, work on site, price of spares)
- injury level of people concerned (from unhurt to killed)
- and others...

Criticality

Along the scale of each criterion, one can determine, or imagine, a probability law (spread of all possible event along the scale, associated with the probability of each event). The criticality of a given event could be considered as the product of its "severity" - according to the various scales discussed - by its probability. Furthermore, the relative importance of criteria which do not have the same measure has to be decided based on policy.

APPLICATION TO INSULATION FAILURE EVENTS

Known causes

Field experience provide examples of possible failures. However, their number is too low to propose relevant statistics and failure rates on switchgear, and the number of samples involved in a given installation is too small to get significance from a failure rate. But, without providing numerical data, some causes are recognised as repetitive and are further discussed here.

It could be noticed also that almost all the failure modes of the high voltage components of an installation, whichever the initial phenomenon, will lead to an arcing fault if not stopped through another diagnosis before. Arc is somehow the ultimate failure mode...

Ageing

Ageing is typically a cumulative process, chemical and/or

mechanical, under permanent stresses like temperature, static loads, service voltage and other ambient conditions. It is unavoidable and difficult to assess. This difficulty leads to either conservative declared life spans or recommended periodic checks when relevant test methods can be applied. It is very difficult to establish the relevancy of a test method intended to appreciate ageing:

- most often, the proposed tests access an information which is already a failure mode, as for example a leakage rate measurement which does not provide the actual information about the decrease of a rubber seal compression ratio; leakage is already a failure mode. In the same idea, the appearance of partial discharges -internal or external- at operating voltage is also a failure mode, but which can be used as a warning against major insulation failure.

- when the test does not diagnose an already existing failure mode, it needs to stress the equipment, or the material, up to its original limit to appreciate the change of characteristic, and such a test is either destructive or at least damaging.

- the challenge could be particularly difficult when considering mechanical properties of components which are not under permanent load - then without possible visible bend or equivalent - but which could fail during an operation.

The recommendation provided by manufacturers are both conservative and based on an average field experience. That means user can be attracted by the idea of keeping in operation installations far beyond their declared life span, but he should also keep in mind that any special condition in the way the installation operates can reduce the margin initially designed. Or the other way round, when a user expect to operate an equipment up to the maximum performances, he has to ensure that the other influent parameters are under control too.

Wear

Wear is considered as loss of material due to abrasion of moving parts; it is observed on mechanisms, leading to abnormal speed or even mis-operation, and on electrical moving contacts, leading to high contact resistance, possible over-heating and, decreased breaking and making capacities. The wear can participate to insulation failure events through either deposit of conductive dust or particles on insulation path, or by compromising the operation performances as stated before.

Wear is part of the criteria when defining the maintenance program of the equipment as, for accessible parts, it can be checked during maintenance. It is also considered when declaring a maximum number of operations for instance, especially for sealed devices. However, for exposed parts, it has to be considered also the possible influence of external conditions, such as dust or humidity, which can affect the wearing process.

Ingress of animals, water, objects...

Such ingress could generate either direct event, as short-circuit between live parts, or cumulative effect, like dust along creepage distances leading to insulation failure. Mastering the conditions around the installation components

is the very first step to be made; it could lead to air conditioning for switchgear rooms for instance, but some easy-to-implement precautions have to be considered as basic (e.g. correct air-flow in the room and well designed openings).

Specifying an adapted Protection Index (IP) for the switchgear is a second step and covers the direct events hypothesis, and some part of the cumulative effects. Such cumulative effects can be checked and corrected during maintenance. Maintenance of switchgear can be a critical issue for dependability, as for availability. When considering the arcing fault risk, the need for busbar maintenance, and the criterion about down-time of the process, it highlights the difficult choice of the installation design, and the associated cost issue. One technical answer on that point could be specifying a GIS switchgear, but then other criteria could be difficult to meet.

Operation abnormalities

Some of the dielectric failures are directly linked to external events, for which the failed equipment could not be considered as responsible. Such events could be either "electrical events" or human interventions.

Among the disturbing events from the electrical network, as load variations and possible overloads, voltage transients and overvoltages, some are clearly out of ranges of the normal parameters - even above the ratings of equipment - and are already some kind of failure by themselves, meaning mistake from design or network operation. These situations should be identified during a proper FMEA procedure, and their occurrence rate, or their probability for triggering an equipment failure, reduced to acceptable level. In that category, attention should be paid to all the known, and sometimes unknown, changes which happen within the installation. It is rather seldom that complete installation study is checked when introducing a new equipment, the influence of which is considered to be negligible. However, along the years, several modifications can be made without challenging the initial hypothesis. It seems to be a recurrent situation when dealing with electrical failures. As the design margins are under pressure because of competition on the initial cost, this point could become even more critical than it has been in the past decades.

An example of such situation could be the harmonic overload of power factor correction capacitors, after the implementation of significant power of electronic power supplies - e.g. variable drives, computers, dimmers -.

When considering how human intervention can trigger an arcing fault, the fact is that the operator is very often either at the very beginning of the sequence, or in such a position that he could have prevented the ultimate failure or its consequences. When looking at the publicly available accident reports involving personnel, it is very often that the main highlighted points focus on lack of procedure, wrong tools and/or wrong operating sequence. Awareness of all parties shall be raised by proper training and information, and safety shall become part of the culture of the companies. Electrical accidents involving casualties are

seldom, especially on indoor installation, and risk awareness of operators is smoothed along the time. Safety rules are very stringent, and under the pressure of other criteria (process continuity, cost...), infringements are quite common. Even if infringement is not the root cause of an electrical accident, it provides clear case of higher rank consequences.

First rank consequences

Arcing fault on liaisons

Cables have a very low failure rate, but can be stressed by their installation conditions (bending radius, static loads...) or damaged by external events. Three core cables are more prone to generate phase to phase faults than single core. In any case, screened cables have a smoother failure mode, as they ensure a low impedance phase to earth fault, easily diagnosed by protection relays (according to earthing system). Cable joints and connectors are critical points; when they are not located in cable compartments of switchgear, they should be protected some way...

The immediate consequences of a cable fault can be mitigated by the installation conditions (possible use of conduits or earthed cable trays for instance), as well as by the neutral management; as these faults can be kept phase to earth by the use of single phase screened cables, the additional selection of a limited ground fault current, through a proper neutral management system, is very efficient as decreasing the possible consequences.

Arcing fault within switchgear

Accidental arcing faults are generally phase to frame, but most often becomes three phase within some tens of milliseconds, with switchboards which are not phase segregated. Three phase faults always generate extensive damage within a switchboard, with partial destruction and general pollution by conductive dust. The containment of the arc within a part of the switchboard, possibly within a compartment, does not ensure that the surrounding parts will be reusable.

Phase segregated switchboards will generate phase to earth fault, with very low probability of multi-phase evolution, depending upon the tightness between phases. They could be considered as a rather good solution regarding behaviour under internal insulation faults, but their design is more complex and significantly larger, then also more expensive. Used in association with a neutral management with high limiting impedance, they could ensure limited overall damages in the event of a fault.

The protection plan should be fast enough to deal with switchgear arcing faults. Protection devices are proposed to limit duration. Internal Arc performance, defined and checked according to standards, provide basic effects mitigation aimed at preventing personal injuries. Consistency shall be ensured between these parameters of withstand time and clearing time, at least for first order failures.

Higher ranks considerations

Meaning of higher rank arcing faults

Based on hypothesis of the existence of some aggravating situation at the time of the fault. That could be:

- a faulty device among those expected to act. Consistency with normal state of the art for protection plans. Same consideration also a basis for rated short time withstand.
- an unusual operating conditions, as open panel for instance.
- a monitoring function which has failed to indicate some out-of-range parameter (e.g. gas pressure).

Changes in the effects of the arcing fault

Changes based on the longer arcing time are linked to protection plan. Proper coordination study provides as short tripping delays as possible. Usually, and considering the hypothesis of fault within switchgear, the conditions can be dealt with through the Internal Arc performance. However, some locations do not have the margin to cover a second order fault condition. Typically, the incoming cable compartment is protected by the upstream circuit-breaker (at the upstream side of the cable), the relay of which is set to coordinate with the incoming breaker of the switchboard. If any problem occurs, the resulting fault duration could be longer than rated performance.

Others changes in effect should be investigated on a case by case basis, and considering also the probability of occurrence.

CRITICITY OF THE VARIOUS SITUATIONS

How to establish a relation between actual fault situations and criticality as discussed previously? The almost unlimited number of possibilities has prevented standards from defining any relevant rule, or test, dedicated to cover such situation. It seems to be currently beyond capabilities to get a mathematical function representative of the "risk level", which means also that it is very difficult, or even impossible, to demonstrate the actual improvement provided by any feature which could be implemented.

A very efficient protection against a non-existing event (e.g. purely theoretical) does not improve the global situation, and any improvement on a highly probable situation will for sure have a positive effect. That means provisions should be taken to work at decreasing the probability of any dreaded events, as well as decreasing their possible consequences, but choices between possibilities remain part of "state of the art".

SOME TECHNICAL POSSIBILITIES TO LIMIT THE EFFECTS, AND THEIR SCOPE OF RELEVANCY

Some are efficient for people safety purpose, some others for damage limitation... The table proposed here below provides some identified possibilities to improve the overall safety of an installation regarding arcing faults. Implementation of such features is not always possible,

even if each of them should be considered as contributive. The column "dependant / independant" refers to the possibility / risk for this feature to become inoperative, due to external condition (e.g. an arc-detection device triggering the breaking operation of a circuit-breaker is a "dependant" feature, as it may be impaired by a power supply problem; a working procedure is a rule, which can always be broken; then it is also "dependant"). As a "dependant" function could open the way for a higher rank failure, it is clear that the so-called "independant" function shall be preferred during the initial design stage.

CONCLUSION

After such a short review of the items which are linked to safety in case of arcing fault, it can be seen that internal arc withstand performance of MV switchboard is contributive to the overall risk management, but should not be considered as a "stand-alone" feature. It can be challenged by other ways of limiting the effects of arcing faults or the exposure to such effects. Design stage of the installation is the most effective stage to consider all possible options and to implement those providing the best cost-effectiveness ratio. As safety is often claimed to be a top priority, it should also be addressed actually this way, as a top priority topic from the very beginning.

Table of possible devices and features contributing to arcing faults mitigation

Device	Feature	Dependant / Independant	Expected added value	Impacted criterion			Known limitations or drawbacks	Criteria to be balanced (i.e. opposed)
				Operator safety	Limitation of damage	Service		
Installation	Limitation of short circuit level	Independant	Lower fault intensity	+	+	=	Multiplication of transformers	Quality of voltage (drops and harmonics)
Installation	Dual circuits in separate locations	Independant	Availability, no need to approach live components	+		+		Initial cost, global size of electrical rooms
Fuses	Current limiting, time limiting	Independant	Limited peak value and duration	+	+		Rating limitations; loss of selectivity	
Supra-conductive limiters	Change impedance under fault conditions	Dependant (?)	Limited r.m.s. value, and possibly peak	+	+			Initial cost, and operation cost. Maintenance.
Switchgear	Phase segregation	Independant	Arcing faults only phase to ground	+	+	=	Little offer available; size of equipment; valid only with adapted neutral management	Reduction of foot-print; functionalities like withdrawability
Switchgear	Arc withstand by design	Independant	Containment of the effects of the arc	+			validated only under normal (static) operation conditions	Size, cost, installation conditions (gas exhaust...)
Arc-killers	Establish a metallic short-circuit	Dependant	limited duration of arcing fault	+	+			Initial cost
Arc detection devices	Speed-up of the protection (C.B.)	Dependant	limited duration of arcing fault	+	+		Fault hypothesis in incoming unit to be covered by upstream CB	
Working procedure	remote operations	Dependant	nobody near the switchgear when operates	+			need for full motorised switchgear	cost, habits