Short circuit behaviour – Surge arresters and counters

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Abstract

By nature, a surge arrester may be overloaded at any time as part of its normal duty. This places tough demands on their ability to "fail safe" and not risk damage to equipment or injury to personnel in the vicinity. Despite this, there remains an uncertainty regarding the true short circuit behaviour of certain designs of arresters and the accessories that are connected in series with them. Since it is impossible to predict when an overload will occur, this raises the question: How safe are they when called upon to pass short-circuit currents?

1   Introduction

A wide variety of parameters influence the dimensioning of a high voltage surge arrester, but the demands as required by a user can typically be divided into two basic categories:

- Protection against overvoltages
- High reliability and a long service life

Additionally and importantly, there is an unstated expectation that the risk of personal injury and damage to adjacent equipment shall be low in the event of an arrester being overloaded.

As the primary requirement for an arrester is to protect under all circumstances, this leads to a natural higher possibility for a failure (overload) compared to other high voltage equipment. The question of "Mean Time Between Failure" (MTBF) and "Mean Time To Repair" (MTTR) is often asked for substation equipment. Other high-voltage equipment, such as circuit breakers, instrument transformers, power transformers, etc., are expected to operate "fault-free" for many years; albeit in conjunction with some form of regular maintenance. However, such an analysis has no meaning or direct relevance for surge arresters. The design-life of a modern gapless ZnO arrester can reasonably be expected to be at least as long as the equipment it is protecting - nominally accepted to be 30+ years. Notwithstanding, this does not mean that it will necessarily last as long as the primary plant. It must be remembered that a surge arrester is, in principle, a sacrificial protective device, designed to operate to protect other electrical equipment and so during the normal course of events it may need to sacrifice itself at any time to protect the primary plant. However, this should not be considered as a "failure" if it occurs for genuine reasons; rather it is the last-resort function of a surge arrester.

The major arrester Standards therefore require testing whereby a deliberate internal short-circuit has been made to check the short-circuit (pressure-relief) capability. Special requirements are set on arresters to ensure that a possible arrester overload will not cause consequential damage to other equipment or injury to personnel.

2   Short-circuit behaviour of HV surge arresters

A correctly selected arrester can divert surges almost endlessly, provided the energy to be dissipated is within the capability of the arrester. In the event that an arrester is required to dissipate more energy than it is capable of, it will sacrifice itself by failing short circuit. Most commonly, arresters are connected phase-to-ground and the resultant earthfault will immediately collapse the voltage on that phase, thereby protecting other equipment on the same phase. The upstream protection will initiate a breaker trip to clear the fault, and the failed arrester can then be replaced.

Surge arrester housings have traditionally been made of porcelain. However, today there is a strong trend, and often even a preference, towards the use of silicone insulators for arresters at all system voltages. There are a number of reasons why silicone is seen as an attractive alternative to porcelain, including potentially better short-circuit capability with increased safety for other equipment and personnel if correctly designed.

It is false, however, to believe that safer short-circuit performance is automatically achieved simply by replacing the porcelain housing with one made of polymer. In the past, there has been the incorrect belief that all polymer-housed arresters, irrespective of design, were capable of carrying enormous short-circuit currents. This is not the case, and the design must be scrutinized carefully for each specific type.

2.1   Hollow tube design

The tubular design incorporates a distinct annular gas-gap between the active parts and the external

insulator. If steps are not taken, there is a likelihood that arresters that contain an enclosed gas volume (both porcelain- or polymer-housed) might explode due to the internal pressure increase caused by the heat generated from a short circuit arc. This leads to the need for these arresters to be fitted with some type of pressure relief system that will open quickly to release the enclosed gas volume to the outside. Such arresters are normally supplied with devices at the top and bottom of each unit, which operate as soon as the internal pressure reaches a certain value. The ionized gas will subsequently be evacuated to the outside of the arrester, and when the two gas streams meet the internal arc will commute to the outside, thus preventing a continual internal pressure increase and avoiding a violent shattering of the housing.

This design is well known and understood. Nonetheless, even if the housing itself does not explode, experience has shown there exists a risk that flange covers, venting ducts, porcelain sheds or other external items can be dislodged and violently cast-off. Mitigation of such a risk must be accounted for in the design and, of course, verified by test.
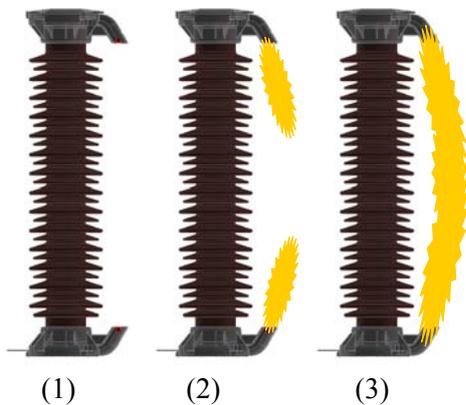

(1)   (2)   (3)

Figure 1.   Operating principle of the pressure relief device of an ABB type EXLIM porcelain housed arrester and HS PEXLIM silicone-housed tube design.

(1) Arrester in its healthy state.

(2) Arrester has internally failed short-circuit, pressure relief plates open and gas begins to be expelled through the venting ducts.

(3) The two gas streams meet and the internal arc is commuted safely to the outside.

There are still many porcelain-housed gapped silicon-carbide (SiC) surge arresters in service worldwide, which by design contain a significant internal gas volume. Since the statistical risk of a malfunction is greater for very old arresters, these can be considered most at risk of failing. Further, when systems expand, there may be a need to upgrade the arresters connected to them, since the result is heavier than designed operating duty and

increased failure risk; a fact that is often overlooked. Arresters manufactured even as late as 1970 may not be provided with any suitable pressure-relief mechanism for safe operation during internal short circuit. Even where such mechanism exists, it may not function satisfactorily if the short-circuit capacity of the line has been increased after the original installation and is now higher than the arrester capability. Such arresters almost certainly would not fulfill today's tough requirements for short circuit safety and would fail violently in the event of their malfunction; causing damage to equipment nearby as well as posing a serious risk of injury to any personnel in the vicinity.

2.2   Closed or wrap design

Surge arresters in this category incorporate a "void-free" (partial or total) polymer housing around the internal assembly, while completely surrounding the active components themselves with hard material. The design is characterized by not including a direct path for externalizing the arc during internal short circuit. Typical solutions include a glass-fibre cloth wound directly on the block column or a separate tube in which the ZnO blocks are mounted. A soft polymer insulator is then fitted (either pre-moulded or directly moulded) over this internal component assembly; often together with grease or gel to fill the interfaces.

In the event of overload, the subsequent internal arc is intended to quickly break its way through the hard material surrounding the ZnO blocks. Thereafter, the arc would easily tear open the soft polymer outer housing in order to release it and the resultant gases.

In order to obtain a good mechanical strength, the cloth/tube must be made sufficiently strong, which, in turn, might lead to a too strong design with respect to short-circuit strength. The internal overpressure could rise to a high value before cracking the hard material, which may lead to an explosive failure with parts being thrown over a wide area. To prevent a violent shattering of the housing, a variety of work-around solutions have been utilized, e.g. slots in the tube. When glass-fibre cloth is used, an alternative has been to arrange the windings in a special manner to obtain weaknesses that may crack. These weaknesses are intended to ensure a pressure relief and commutation of the internal arc to the outside; thus preventing an explosion.

One may nevertheless question the ultimate effectiveness of such solutions in relation to their ability to function consistently as intended,

independent of how and where the internal arc is initiated. In particular, if the arrangement is made too closed, such that pressure can build up to a significant level, the design may act more as per the tube design and warrant the need for a separate pressure relief device.

2.3 Open or cage design

This design may consist of loops of glass-fibre, glass-fibre rods or a cage of glass-fibre weave around the block column. What defines this type of design is that the active components are not fully enclosed by hard materials. Instead, a body of soft polymer material directly surrounds the internal components. Such designs lack enclosed gas volume. Should the arrester be stressed in excess of its design capability, an internal arc will be established. Due to the open design, the arc will tear or burn its way through the polymer material, permitting the arc, along with any resultant gases, to escape quickly and directly. Hence, separate pressure relief devices are not required for this type of design.

Nevertheless, the arrangement should not be too open; otherwise there is a risk that fragments of hard internal material – notably ZnO blocks and metal spacers - could be expelled together with the arc. This is particularly of concern in the case of a long arrester unit in combination with high short-circuit currents.
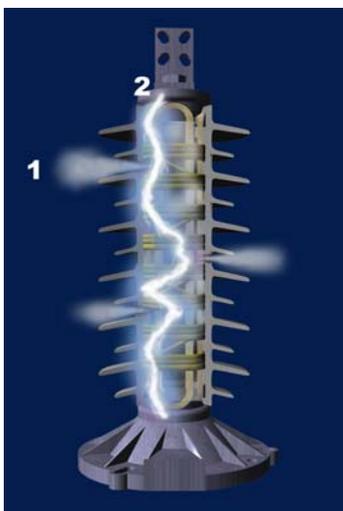

Figure 2.   Operating principle of " pressure relief" for an ABB type PEXLIM directly-moulded open-cage design.

(1) Arrester has failed short-circuit and gas begins to be expelled through the soft silicone housing.

(2) The gas streams trigger an external flashover and the internal arc is commutated safely to the outside. At the same time, the belt-winding holds the internal components in place.

ABB employs a unique, patented design for its PEXLIM arrester to enclose the ZnO blocks of

each module under pre-compression in a cage formed of glass-fibre reinforced loops fixed between two yokes that form the electrodes. A special flame-resistant fibre is then wound over the loops, resulting in an open cage design for the module. The outer housing of silicone is thereafter moulded directly onto the internal components to form a void-free, sealed housing along the entire length of the insulator. The result is an arrester with secure sealing, high mechanical strength and, importantly, excellent short circuit performance, thanks to the fibre-windings preventing explosive expulsion of the internal components.

A significant amount of development work has been undertaken by ABB to determine the appropriate amount and angle of the fibre-winding in order to withstand short circuit currents consistently in a safe and robust manner. The conclusion reached is that a belt-arrangement is seen as a necessity with this design for long unit-modules used in high voltage applications.

Figure 3.   Successful short circuit test on PEXLIM surge arrester with belt-winding.

Figure 4.   Failed short circuit test during trial without belt-winding.

3   Short circuit (pressure relief) tests

Standardized short circuit test procedures within the major arrester standards take into consideration what might happen at failure of the ZnO blocks for individual designs to minimize the risk for damage to surrounding equipment and personnel. However, there remains a differentiation in requirements between current editions of the two most common arrester standards IEC60099-4 and IEEE C62.11. These differences as they are today can be summarized as follows:

IEC 60099-4
- Test procedure well specified for different designs and housing types.
- Includes high, intermediate and low test currents.
- Clear distinction made regarding specific requirements particular to polymer arresters.

3

IEEE C62.11
- Same test procedure and failure mode (fuse wire) defined for both porcelain and polymer housed station and intermediate arresters. Only high and low current test required.
- Different procedures for distribution type porcelain- and polymer-housed arresters. Includes different mode of failure for high, intermediate and low test current only for polymer-housed distribution arresters.

IEEE C62.11 is in the process of being reviewed with consideration to the IEC requirements. The latest IEC Standard is hence more up-to-date than its IEEE counterpart is, since it takes into account a number of concerns and deficiencies in previous editions that have not yet been addressed by IEEE.

3.1   Classification of arrester designs

Two basic designs, designated "Design A" and "Design B", have been defined in IEC 60099-4. They differ in the relative volume of an enclosed gas channel that runs along the length of the arrester.

Arresters with "Design A" have a gas channel running along the entire length of the arrester unit and fills $\geq$ 50% of the internal volume not occupied by the internal active elements. Typically, these arresters are porcelain-housed or polymer-housed with a composite hollow insulator incorporating an annular gap, i.e. tubular design.

Arresters with "Design B" are of a solid design with no enclosed volume of gas or having an internal gas volume filling < 50% of the internal volume not occupied by the internal active elements. Typically, these are void-free polymer-housed arresters without any separate pressure relief device, i.e. open, cage, closed or wrap design.

3.2   Test procedure

The performance of a surge arrester under short-circuit is very much a matter of statistical risk and probability. Hence, a single round of testing – whether successful or otherwise – cannot guarantee with certainty the repetitiveness in service. For this reason, ABB undertakes a significant number of short-circuit test sequences during the design-development stage before selecting a final solution. In this way, the probability is increased that the arrester will truly function consistently as expected. As an important part of this, it is seen as crucial to make tests on

the longest unit housing, since testing shorter housing lengths does not directly correlate to performance at full length.

There has been a lot of discussion over the years whether the short-circuit test current should be initiated by a fuse wire along the ZnO block surface, a fuse wire through a drilled hole in the centre of the ZnO blocks or by pre-failing (electrical overloading). A short-circuit test has to consider worst-case scenarios, but at the same time the test should represent the most relevant failure scenario without placing too harsh/simple requirements on the design.
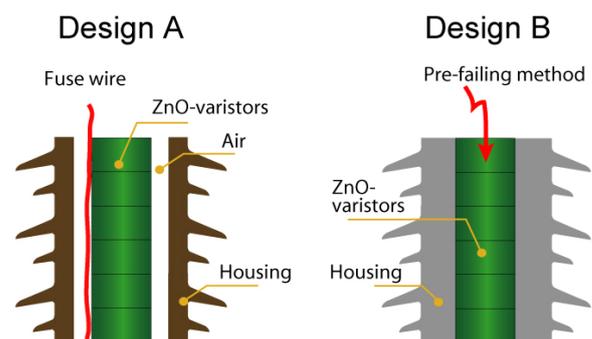

Figure 5.   Comparison of modes for short-circuit initiation.

For "Design A" arresters, it is generally agreed that the fuse wire in the gas volume along the surface of the ZnO block column represents the most relevant failure scenario. For this design, the probability of a failure initiated in the gas volume is much higher than in the ZnO blocks, and hence this design has mainly to prove its ability to handle the shock wave caused by the internal arc.

For "Design B" polymer-housed arresters, there is a higher probability of failure initiated in the ZnO blocks and a fuse wire along the block surface can generally not be accepted since this does not represent the worse case scenario for this design (too simple) and may result in unsafe arresters being considered reliable from a short-circuit point of view. On the other hand, a fuse wire through holes drilled in the blocks is conversely a too harsh scenario for this kind of arrester, as it extremely unlikely that all ZnO blocks of a failing polymer arrester with this design will be punctured. It is therefore justified to specify the pre-failing method for "Design B" polymer-housed arresters, which among the alternatives gives a reasonable compromise with regard to test severeness and realism, and it automatically covers possible influences of material homogeneity. A homogeneous ZnO block may thermally fail closer to the centre, compared with a non-homogeneous block being potentially weakest nearer the edge. Regardless, the pre-

4

failing method verifies performance as would likely occur in service for this type of arrester.

The required arrangement for connection of the test circuit itself is also clearly defined and specified within IEC 60099-4 to be in such a manner that would represent the worst-case scenario for a particular design.

3.3 Test currents

In the past, it was taken for granted that an arrester fulfilling a certain current class with respect to pressure relief capability automatically also fulfilled all lower current classes. It was subsequently realized that this was not always the case, and a design may include "grey zones" if it is only tested against the highest possible current amplitude. Very long units may effectively commute the arc to the outside when extremely high currents are involved, but fail violently at lower currents. In order to avoid this uncertainty, IEC 60099-4 requires that arresters must not only be tested with the highest short-circuit current (100%), but also at approximately 25 % and 50 % of the highest current. In addition, a low current test shall also be performed.

The IEC standard furthermore details the requirements for test durations and peak current levels valid for a particular design. In particular, the requirements permit arresters to be tested in full length, which is seen as significant to verifying true short circuit behaviour.

3.4 Test evaluation

The basic pass criteria are that no violent shattering occurs and open flames shall be self-extinguished within 2 minutes. However, for practical reasons, it is considered unrealistically hard to have such requirements as "remain completely intact" or "no piece shall be ejected" as the pass criteria for surge arresters undergoing short-circuit tests. These would judge the arrester as having failed, despite the overall performance being positive. IEC 60099-4 hence permits fragments of ceramic material (ZnO block or porcelain) of up to 60 g in weight, pressure relief vent covers and soft parts of polymeric materials to fall outside the test enclosure.

One can well accept that soft polymeric materials can do little or no damage should they be cast off. ABB, nonetheless, is critical of the Standard's acceptance that hard material weighing as much as 60 g may be ejected a significant distance from the arrester. This is seen as a compromise to cater for fragments of hard material such as porcelain or ZnO blocks that just jump over the test enclosure without any dangerous kinetic energy.

The deficiency is that no distinction is made with such fragments that are explosively ejected during the test. A 60 g piece of ceramic material, when thrown with sufficient force, can result in serious damage or injury. It is therefore seen as important that the difference is understood between "non-shattering" and "non-explosive". Hence, even if the fragments are less than 60 g in weight, the additional criteria should be that there is not an explosion that leads to a violent expulsion of hard material outside of the test enclosure. For example, an arrester that has exploded with such force that ceramic material is completely pulverized to the extent that only pieces weighing less than 60 g remain cannot be considered, with good conscience, to have successfully passed the test.

4 Surge counters are in the same circuit

For system voltages above approximately 100 kV, surge counters are often installed in series with the surge arresters. The main reason for the use of surge counters on modern gapless ZnO arresters is to check if a particular transmission line or phase suffers from an exceptionally high number of overvoltages leading to arrester operation - lightning faults on a line, for example. If this is the case, whilst it validates the need for the arresters, use of some preventative counter-measures may be warranted to limit the number of surges. A sudden increase in the counting rate may also indicate an internal arrester fault, in which case the arrester should be investigated further. Surge counters are sometimes complimented with the facility to measure leakage currents (total and/or resistive), with the intention of monitoring and diagnosing the condition of the arrester and its state of fitness for continued service.

By nature, these surge counters/monitors must be connected in series with the surge arresters in order that they will see the same surges and currents that the arrester does. This means that they will also be exposed to the same short-circuit currents in the event of an arrester overload. However, at present, there are no requirements in the Standards for any form of testing or verification of this device's ability to safely withstand the duty to which the arrester may be subjected. Since it is impossible to predict when an overload will occur, this raises the question: How safe are they when called upon to pass short-circuit currents?

In order to generate the necessary input into the registry circuit with passage of surge current to earth, one of two basic designs is used in counters

on the market today; either

- incorporating ZnO blocks and/or a spark gap. In some cases, these also protect the metering section from damage during the application of high currents.

- incorporating an impulse current transformer. In some cases, a separate zero-flux current transformer is included for leakage current metering.

The first design with ZnO block or spark gap has the benefit of being cost-effective and simple. They do, however, have the disadvantage of adding additional residual voltage in the protective circuit formed by the arrester and counter, leading to an increase in the voltage seen by the protected object at every surge. But of greater concern from a short-circuit safety point of view is the risk of explosive failure during passage of high short-circuit, since the voltage generated across the ZnO blocks and/or spark-gap can be excessive; leading to failure and consequential internal arc. A rapid expulsion of the internal components can be the result unless the device has some auxiliary pressure relief function. For the most part, these devices are completely sealed and encapsulated to prevent moisture ingress, which puts their safe short-circuit behaviour in doubt.
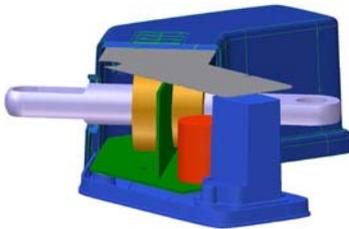

Figure 6.   Internal design of ABB type EXCOUNT-II surge monitor.

The second design utilizes a toroid current-transformer in conjunction with a pass-through primary winding. There is therefore no voltage generated, neither during passage of surge current nor full short-circuit in the event of an arrester overload. The risk for a violent explosion is hence negated. ABB's range of EXCOUNT surge counters/monitors are of this design, and their exceptional short-circuit safety has been well verified in test. The use of suitably dimensioned conductors on EXCOUNT ensures that they also remain intact; something that the user should even consider when selecting the connecting cables.

Regardless of the design, some form of short-circuit testing would seem warranted to verify performance of the counters. Lack of such a requirement in the Standards is considered a

serious deficiency, since an exploding counter can do equally as much damage as an arrester. In fact, considering surge counters are typically mounted at eye-level and, most often, the operator must stand directly in front in order to read the values, this makes them potentially even more dangerous than an arrester from a personnel safety point of view. One notable exception is ABB surge monitor type EXCOUNT-II which, together with its inherently safe design, has the ability to be read from a remote distance.

It would seem justified that since the counters can be subjected to the same duty as the arrester, that they should be tested in the same way and with the same acceptance criteria, i.e. a test sequence with different short circuit currents applied and the pass criteria that no violent shattering or explosion occurs and open flames shall be self-extinguished within 2 minutes.

5   Conclusions

The surge arrester market has taken well to the use of polymer-housings; not least because of their promise of improved and safer short-circuit performance. Nonetheless, the user should not expect nor accept that this will be the case simply because of a change in housing material or that a certain type of manufacturing method is used. The design must be scrutinized as a whole and results from applicable and appropriate testing analyzed in order to make the final judgment concerning short-circuit safety. This applies not only to the surge arresters themselves (both porcelain- and polymer-housed), but also the accessories which are connected in series with them.

Surge arresters with significant internal gas volume must be provided with quick operating and effective pressure relief devices. Polymer-housed arresters of solid design cannot be too closed nor too open, otherwise their explosion can result in hard materials being violently expelled over a wide area. Similarly, accessories such as surge counters/monitors should not be of a design that inherently makes them less safe than the arresters to which they are connected.

6   References

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