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GUIDE FOR APPLICATION OF IEC 62271-100 AND IEC 62271-1

PART 1
GENERAL SUBJECTS

Working Group A3.11

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Members: F.J. Amon (Brazil), J.-M. Biasse (France), J.Y. Blanc (France), A. Bosma (Sweden), D. Dufournet (France), D. Fuechsle (Switzerland), S.M. Ghufran Ali (United Kingdom), E. Haginomori (Japan), R. Jeanjean (France), S.L. Jones (Australia), S. de A. Morais (Brazil), I.D. Naylor (United Kingdom), J. Pasteau (France), D.F. Peelo (Canada), H. Peters (Germany), J. Reid (United Kingdom), H.-H. Schramm (Germany, convenor), H.M. Smith (USA), S. Théoleyre (France), Z. Vostracky (Czech Rep.), Ch. Wagner (USA), M. Waldron (United Kingdom).

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1 Introduction

Questions arise frequently concerning the basis and interpretation of standards IEC 62271-100 [1] and IEC 62271-1 [2]. In most cases, these questions were due to a lack of background knowledge of the values and requirements laid down in these standards.

One of the objectives of CIGRE is to establish the scientific foundations for standardisation. Many of these values and requirements were originally based on investigations carried out in CIGRE Study Committee A3 "High Voltage Equipment". Therefore, as the need for an application guide for these standards became more and more apparent, CIGRE SC A3 decided to develop such an application guide. CIGRE WG A3.11 was entrusted with this task, and produced this document on behalf of CIGRE and IEC.

This application guide addresses utility, consultant and industrial engineers who specify and apply high-voltage circuit-breakers, circuit-breaker development engineers, engineers in testing stations, and engineers who participate in standardisation. It is intended to provide background information concerning the facts and figures in the standards and provide a basis for specification for high-voltage circuit-breakers. Thus, its scope will cover the explanation, interpretation and application of IEC 62271-100 and IEC 62271-1 as well as related standards and technical reports with respect to high voltage circuit breakers. However, it is not intended to be used as an electrotechnical training course or to replace textbooks.

A selected number of reference textbooks are listed below. It must be remembered that the technology of high-voltage circuit-breakers is continuously progressing and will continue to do so in the future. Therefore, it is advisable to use such textbooks primarily as a source of information on network behaviour, such as switching conditions, transients, etc., and not for switchgear design.

As the installation of standard equipment in general is more economical than special designs, the application guide will help the utility and industrial engineers in the selection of the appropriate ratings to conform to their needs and specifications. It will enable them to judge which rating is necessary when specifying their circuit-breakers. This should take into account that in future high-voltage networks which will be worked harder and closer to their limits and that high-voltage circuit-breakers of present day technology are designed and procured for a lifetime of several decades. It is recognised that certain conditions may necessitate requirements which are outside the circuit-breaker standards. In such cases, the Application Guide will help to specify the various ratings or possible additional testing to achieve the most economical solution.

Standards should be written fit for purpose, i.e. they should reflect general system requirements to ensure that the installed equipment works properly. Although it is recognised that not 100 % of all conditions occurring in service can be covered, long term experience with high-voltage switchgear standards shows that system conditions are generally covered adequately. Nevertheless, the feedback from service and new developments in equipment and networks must be taken into account in their revision, making standardisation an ongoing process. The Application Guide will be a forum to provide the necessary information concerning the background of changes in the standards.

Technical specification aspects are not generally considered in standards. However, this application guide will address such aspects where appropriate.

1.1 Circuit-breaker history

Circuit-breakers are one of the great inventions of the 20th century enabling the power systems of today and their contribution to modern society. The various circuit-breaker types were developed over overlapping periods with each taking a number of years before reaching commercial application.

The earliest circuit-breakers were of the bulk oil type with the first, those of Kelman in the early 1900s, consisting of a crude arrangement of switches in separate wooden barrels connected in series and gang operated. Bulk oil circuit-breakers evolved over the next 30 years, the principal developers in the United States being Slepian of Westinghouse and Prince and Skeats of General Electric. In Europe, bulk oil circuit-breakers reigned until the early 1950s and then were totally supplanted by minimum oil circuit-breakers. Bulk oil circuit-breakers are in use up to 360 kV with eight breaks in series, while the minimum oil type are used up to 420 kV with up to ten breaks in series. Some utilities actually continued acquiring these types of circuit-breaker into the 1990s.

The development of air-blast circuit-breakers took place in Europe, first by Whitney and Wedmore of the British Electrical Research Association in 1926 with further development in Germany and Switzerland in the 1930s and 1940s. These circuit-breakers came into prominent use in the 1960s and in fact became the enablers of EHV systems at 500 kV and above. Air blast circuit-breakers were manufactured into the early 1980s when they were supplanted by the lower cost and less complex SF_6 puffer type circuit-breakers. Air magnetic circuit-breakers are a variation of air-blast circuit-breakers in use at medium voltages up to 52 kV.

Already in the 1930s SF_6 gas was recognized for its unique dielectric properties (patent by F.S. Cooper of General Electric on its use in capacitors and gas insulated cables). The use of SF_6 gas for current interruption was patented by H.J. Lingal, T.E. Browne and A.P. Storm of Westinghouse in 1951 but the first SF_6 circuit-breakers did not appear on the market until around 1960. These circuit-breakers were of the dual pressure type based on the axial blast principles used in air-blast circuit-breakers and had a relatively short manufacturing life span to about 1980. Puffer type SF_6 circuit-breakers (often referred to as single pressure SF_6 and actually based on a principle invented by Prince and used in the so-called impulse type bulk oil circuit-breaker where the oil flow was produced by a piston driven by the operating mechanism) were developed in the 1970s and rapidly supplanted the dual pressure type. Further evolution of SF_6 circuit-breakers has led to rotating arc technology up to 72,5 kV and self-blast technology above 72,5 kV both of which have the advantage of requiring lesser transmission of energy from the operating mechanism to the interrupters and thus lower energy and simpler mechanisms.

Work on vacuum interrupters also started in the 1920s but commercial circuit-breakers appeared first in the 1960s. At present vacuum circuit-breakers are in common use at medium voltages only.

The application timelines for six major circuit breaker types is shown in Figure 1.

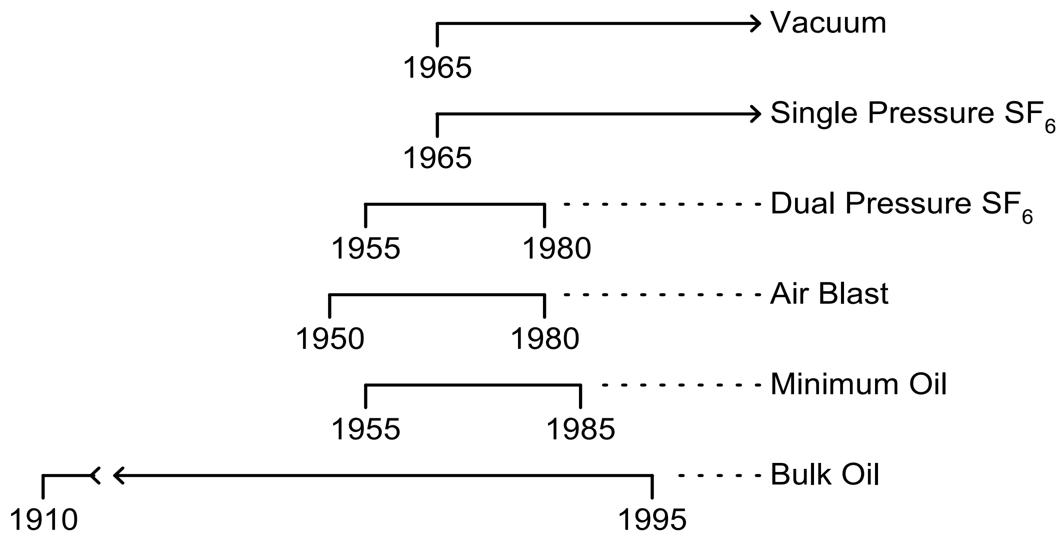

Figure 1 - Timelines for application of different circuit-breaker types.
Solid lines indicate approximate or ongoing manufacturing periods

1.2 Evolution of IEC standards for high-voltage circuit-breakers

As high-voltage transmission and distribution systems and high-voltage circuit-breakers developed it was found necessary to provide standards for circuit-breakers, first on national basis. For example, already in 1923 the first edition of the British Standard B.S.S. No. 116 for circuit-breakers was issued.

In the late 1920s it was recognized that an international agreement should be obtained for a specification for high-voltage circuit-breakers, particularly with respect to their behaviour under short-circuit condition. This lead to the establishment of the "IEC Advisory Committee No. 17" which met for the first time in Stockholm in 1930 and drafted some preliminary recommendations on the international standardisation of circuit-breakers.

After a series of specially convened meetings the first IEC Specification No. 56 for Alternating-Current Circuit-Breakers, Chapter I, Rules for Short-Circuit Conditions, was issued in the summer 1937, with international approval and recognition as a basis upon which to establish national specifications.

Also at that time, already, the need was seen to have Certificates of Ratings issued by approved Testing Authorities to confirm the compliance with Standard Specifications.

The second world war interrupted the further work on the IEC circuit-breaker standards. In 1954 the second edition was published which used and continued the concept of the first edition. It was intended that the IEC Specification No. 56 should ultimately incorporate five chapters which were to be discussed in the following order:

Chapter I	Rules for Short-circuit Conditions.
	First edition of Publication 56 to be revised and enlarged in a second edition.
Chapter II	Rules for Normal-load Conditions.
	Part 1 – Rules for Temperature-rise.
	Part 2 – Rules for Operating Conditions.
Chapter III	Rules for Strength of Insulation.
Chapter IV	Rules for the Selection of Circuit-breakers for Service.

Chapter V Rules for the Maintenance of Circuit-breakers in Service.

Actually, the second edition, as the first one, did not progress beyond Chapter I. It was bilingual and had a total of 77 pages. According to its scope it covered circuit-breakers of 1000 V and above.

Some major features were:

- The breaking capacity was expressed in MVA by 2 values, one for a symmetrical and the other for an asymmetrical breaking current;
- The TRV, defined as "restriking voltage", was of single frequency. The amplitude factor or crest value and the TRV frequency or rate-of-rise were not specified but to be evaluated in the tests;
- The first-pole-to-clear factor in general was 1,5. However, in a note allowance was made to use 1,3 for circuit-breakers for earthed systems;
- 50 Hz and 60 Hz were no problem, as for making and breaking tests the tolerance of the frequency was ±25 %;
- The short-circuit current breaking tests consisted of test-duties 1 to 5 with 10 %, 30 %, 60 % and 100 % of the rated symmetrical and the rated asymmetrical breaking current.

Edition 3 was issued in 1971 with a new structure. It applied to high-voltage a.c. circuit-breakers rated above 1000 V and had six parts which were published as separate booklets:

Publication 56-1:	Part 1: General and Definitions.
Publication 56-2:	Part 2: Rating.
Publication 56-3:´	Part 3: Design and Construction.
Publication 56-4:	Part 4: Type Tests and Routine Tests.
Publication 56-5:	Part 5: Rules for the Selection of Circuit-breakers for Service.
Publication 56-6:	Part 6: Information to be Given with Enquiries, Tenders and Orders and Rules for Transport, Erection and Maintenance.

In total Publication 56 consisted of 294 pages when it was issued, but over the years a large number of amendments was added. Out-of-phase was covered by its own Publication 267.

The third edition was the first comprehensive IEC Standard on high-voltage circuit-breakers meeting the originally intended goals. It included, also, the general requirements which are now compiled in IEC 60694.

Compared to the second edition a large number of changes were introduced:

- For the first time mechanical tests, tests on insulation properties, tests on auxiliary and control circuits, temperature rise tests, etc., were specified.
- The R 10 series is used for rated normal and breaking currents.
- The TRV (first time to use this term) representation by two or four parameters and the definitions as used up to today are installed.
- For rated voltages up to 100 kV the first-pole to clear factor is 1,5, for 123 kV and above it is alternatively 1,3 or 1.5.
- The supply side rate-of-rise of TRV for 123 kV and above for terminal fault is 1,0 kV/μs for TD 4, 2,0 kV/μs for TD 3 and 5,0 kV/μs for TD 2.
- The short-line fault is introduced. The specified surge impedance is 480 Ω for lines with 1 conductor/phase (52-245 kV, < 40 kA), 375 Ω for 2 conductors/phase and 330 Ω for 3 or 4 conductors per phase. The line side peak factor is 1,7, 1,6, or 1,5, respectively. The source side rate-of-rise is 0,67 kV/μs.

- Test for capacitive current switching (line and cable charging, single capacitors) are prescribed.
- Not only type tests, but also routine test procedures are defined.

Basically, edition 4 of IEC 56, issued 1987, followed the scheme of the 3rd edition. However, to avoid a duplication of requirements in the various standards for high-voltage switching equipment Publication 56 was reduced to those which were specific for high-voltage a.c. circuit-breakers. The "common clauses for high-voltage switchgear and controlgear" were published in IEC 694.

Edition 4 of IEC 56 consisted of one book of 329 pages. To conform with actual service conditions some major changes were incorporated:

- As all systems rated 245 kV and higher are earthed only a first-pole-to-clear factor 1,3 is specified for these voltage levels. For 100 to 170 kV alternatives 1,3 and 1,5 are specified.
- Based on a large number of network investigations the supply side rate-of-rise of TRV is increased to 2,0 kV/µs for 100 %, 3,0 kV/µs for 60 % and 5,0 kV/µs for 30 % rated breaking current.
- To take into account the clashing of the conductors of a line phase due to the forces of the short-circuit current, which makes it similar to a single conductor, a uniform surge impedance of 450 Ω is specified for all short-line fault tests. The line side peak value is 1,6, the supply side rate-of-rise 2,0 kV/µs.
- The ITRV (initial transient recovery voltage) is introduced for rated voltages of and above 100 kV.
- Out-of-phase specifications are included.
- To prove that capacitive current breaking is performed without restrikes the number of tests per duty is increased.
- Also, the number of operations during mechanical type tests is increased from 1000 to 2000.

And still, Publication 56 continued to grow. The 5th edition, issued in 2001 and under the new numbering system designated IEC 62271-100, has 575 pages. The remains the same but its content was revised taking into account service experiences and requirements by the utilities:

- Classifications of circuit-breaker are introduced with respect to mechanical and (for medium voltage) electrical endurance and restrike behaviour when switching capacitive loads.
- More severe test conditions are prescribed for circuit-breakers to prove a very low probability of restrikes in capacitive current switching.
- For type tests the number of test specimen is limited.
- Some test procedures are prescribed in more detail.
- Critical current tests and single-phase and double-earth fault tests are treated in particular.
- Tolerances are given on practically all test quantities during type tests.
- Alternative d.c. time constants, longer than 45 ms, are specified for the different levels of rated voltages.

In the course of the work on the 4th edition of IEC 56 it was decided to compile all specifications which were common to the various types of high-voltage switchgear and controlgear in an own standard. This avoided their repetition in the individual equipment standards. Thus, the first edition of IEC Publication 694 "Common clauses for high-voltage switchgear and controlgear standards" was issued in 1980. It covered the equipment falling under the responsibility of subcommittees IEC SC 17A and SC 17C, such as circuit-breakers, disconnectors and earthing switches, switches and their combinations with other equipment, gas-insulated substations, etc. Mainly, these specifications concerned normal and special service conditions, ratings and tests on dielectric withstand, normal and short-circuit current carrying auxiliary and control circuits, and common rules for design and construction. This first edition had 78 pages.

The experience with this standard on common specifications was very positive. Therefore, when the decision was made to revise IEC 694 this was largely to take into account items which had not been covered by standards, so far. Very little had to be changed or updated in the existing clauses of the first edition. This second edition with title "Common specifications for high-voltage switchgear and controlgear" published in 1996, has, among others, additional chapters which deal with safety aspects of electrical, mechanical thermal and operational nature. This had, in particular, consequences for the rules for design and construction as well as tests which now, also, covered topics such as interlocking, position indication, degree of protection by enclosures and tightness. A new and important item that was introduced was electromagnetic compatibility (EMC). Naturally, service and test experiences which had been gathered on the basis of the first edition reflected in the revision. For example, the number of test specimen became limited, the conditions for identification of the test object became more pronounced, and the criteria to pass the test were written in a more exact manner.

Manufacturers, users and test laboratories recognize that the reliability of high-voltage switchgear is of crucial importance for the safety and availability of the supply of electric energy. The overall high level of reliability and performance which is common today has its roots in the very good quality of the standards for high-voltage switchgear and controlgear. They are continuously updated to reflect the actual status of the respective technologies.

1.3 References

[1] IEC 62271-100, 2001: High-voltage switchgear and controlgear – Part 100: High-voltage alternating current circuit-breakers

[2] IEC 62271-1, [1]: High-voltage switchgear and controlgear – Part 1: Common specifications

1.4 Bibliography

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Roberto Colombo: Disjuntores em sistemas de potencia (port.). Nobel, Sao Paulo: ISBN 85-213-0381-5

Editor: Manfred Lindmayer: Schaltgeräte, Grundlagen, Aufbau, Wirkungsweise. Springer Verlag, Berlin: ISBN 3-540-16706-4. New York: ISBN 0-387-16706-4.

Lou van der Sluis: Transients in Power Systems, John Wiley & Sons, Ltd, ISBN 0-471-48639-6.

[1] To be published

2 Classification of circuit-breakers

The IEC 62271-1 and IEC 62271-100 subclauses relevant to this chapter are:

3.4.112	Circuit-breaker class E1
3.4.113	Circuit-breaker class E2
3.4.114	Circuit-breaker class C1
3.4.115	Circuit-breaker class C2
3.4.116	Circuit-breaker class M1
3.4.117	Circuit-breaker class M2
4.110	Number of mechanical operations
4.111	Classification of circuit-breakers as a function of electrical endurance
6.101.2.3	Description of the test on class M1 circuit-breakers
6.101.2.4	Extended mechanical endurance tests on class M2 circuit-breakers for special service requirements
6.111	Capacitive current switching tests
6.112	Special requirements for making and breaking tests on class E2 circuit-breakers
8.104	Selection for electrical endurance in networks of rated voltage above 1 kV and up to and including 52 kV

When drafting a call for tender, there are two particular questions concerning the classification of the circuit-breakers:

- what is its application in the network?
- what is the anticipated frequency of operation of the circuit-breaker?

2.1 Application of the circuit-breaker in the network

This question is specifically relevant in the case of a customised purchase. In the case of a general contract, the question must be considered in economic terms of the purchase of circuit-breakers for general or for special applications.

The ratings of a circuit-breaker are summarised in subclause 4 of IEC 62271-100.

Items a) through o) in subclause 4 of IEC 62271-100 give the characteristics common to all the circuit breakers, while items p) through w) the specific characteristics for circuit-breakers intended for special application.

2.2 Anticipated frequency of operation of the circuit-breaker

There are three duties where options exist: mechanical operations, electrical endurance and capacitive current switching operations.

2.2.1 Mechanical operation: class M1and M2

The two classes of mechanical endurance are defined in 3.4.116 and 3.4.117 of IEC 62271-100.

As a general rule, the number of operations of high-voltage circuit-breakers switching transmission lines is relatively small, and class M1 is sufficient.

For particular applications, such as frequent switching of reactors, capacitor banks, industrial applications, specification of class M2 is recommended.

The type test requirement of class M2 does not necessarily demonstrate a superior reliability over class M1 for the same circuit-breaker design unless apparent unreliability can be clearly related to a high frequency of use of the circuit-breaker.

It may be more appropriate to perform the requirements for class M1 type tests on a number (greater than one) of samples of a particular design of circuit-breaker.

It must be noted that it is always possible, in the case of a very special use (pumping station, etc.), to request a larger number of operations than that recommended for class M2.

2.2.2 Electrical endurance: class E1and E2

The two classes of electrical endurance are defined in 3.4.112 and 3.4.113 of IEC 62271-100.

There is no requirement for electrical endurance for circuit-breakers at voltages ≥ 52 kV.

IEC 62271-310 proposes a test procedure for electrical endurance tests (class E2) for rated voltages ≥ 72,5 kV.

2.2.2.1 Distribution network

Generally, class E1 circuit-breakers are adequate.

It is normal for the class E1 distribution circuit-breakers that type tests are carried out on a single circuit-breaker sample without maintenance, which in itself is an electrical endurance test.

Class E2 is only justified for special applications (e.g. frequent fault occurrence, pumping stations, capacitor banks, etc.) or for similar applications where increasing the number of operations, or extending the interval between maintenance operations, is an economic choice to be made by the user.

2.2.2.2 Transmission network

An electrical endurance test may be justified for special networks (e.g. high frequency of faults) or for extending the interval between maintenance operations. This is an economic choice to be made by the user.

2.2.3 Capacitive current switching operations: class C1 and C2

The two classes of restrike performance defined in subclauses 3.4.114 and 3.4.115 of IEC 62271-100.

The term "restrike-free" has been deleted from the standard because it did not correspond to a physical reality.

The standard introduces the term of "restrike probability" during the type tests, corresponding to a certain probability of restrike in service, which, as explained in Annex J of IEC 62271-100, depends on many parameters. For this reason the term cannot be quantified in service.

The main differences between class C1 and C2 type tests are:

- the test sequence for class C1 is 0/48 or 1/48+0/48;
- the T60 wear test before class C2 type tests;
- the test sequence for class C2 is 0/96 or 1/96+0/96 for line and cable switching;
- the test sequence for class C2 capacitor bank switching is 0/48 + 0/120.

It must be noted that during the type tests, the number of restrikes may be influenced by the source energy, which is responsible of the possible damages within the interrupting unit.

The choice for the user between class C1 and C2 depends on:

- the service conditions;
- the operating frequency;
- the consequences of a restrike (for cable systems, the influence of restrikes is negligible compared to the influence of restrikes in overhead transmission lines).

Class C1 is acceptable for medium voltage circuit-breakers and circuit-breakers applied for infrequent switching of transmission lines and cables.

Class C2 is recommended for capacitor bank circuit-breakers and those used on frequently switched transmission lines and cables.

2.2.4 Combination of classes

To fully specify a circuit breaker, three types of "endurance" classes have to be defined in combination.

It must be noted that these three classes are not totally independent.

For example:

- a circuit-breaker that is operated frequently (e.g. capacitor bank switching) will probably belong to classes M2/C2/E1 or M2/C2/E2 depending on the station protection arrangement;
- a circuit-breaker intended for frequent switching of transmission lines will probably belong to classes M1/E2/C2.

2.3 Conclusion

A circuit-breaker is defined by its complete rating, i.e. the basic short-circuit rating and, for example, with or without out of phase switching, with or without overhead line capacitive current switching as well as by the endurance classification such as E1, M2, etc.

It is the technical and economic responsibility of the user to select the type of circuit-breaker and its endurance classes according to:

- the technical needs, derived from the point of application and the proposed usage on the user’s system;
- the management of the user’s circuit-breaker population;

- the user's maintenance policy, which is increasingly linked to the system availability and life cycle costs;
- the cost of the circuit-breakers, with preference for the purchase of standard circuit-breakers.

3 Normal current and temperature rise

3.1 General

This section of the guide also applies to other switchgear and controlgear components of similar basic construction to circuit-breakers and hence it is written making reference to switchgear and controlgear rather than circuit-breakers alone.

The IEC 62271-1 and IEC 62271-100 subclauses relevant to this chapter are:

4.4 Rated normal current and temperature rise

6.5 Temperature rise tests

8.102.4 Selection of rated normal current

3.2 Load current carrying requirements

3.2.1 Rated normal current

The switchgear and controlgear is designed for applications where the load current does not exceed the rated normal current under specific conditions. These conditions are:

- the altitude above sea level for the application is 1000 m or less;
- the ambient temperature does not exceed 40°C and the average value, measured over a period of 24 h, does not exceed 35 °C.

NOTE The rated normal current does not need to be corrected for altitudes up to 2000 m.

When choosing the switchgear and controlgear for an application the following parameters should be taken into account:

- the expected maximum load current. The rated normal current of the switchgear should be selected from the R10 series, specified in IEC 60059 [1].
- the expected maximum ambient temperature around the switchgear. For ambient temperatures up to 40 °C no special requirements are given.

3.2.2 Load current carrying capability under various conditions of ambient temperature and load

3.2.2.1 General

The rated normal current is based on the maximum permissible total temperature limitations of various parts of the switchgear and controlgear when it is carrying rated normal current at an ambient temperature of 40 °C. The total temperature of these parts under service conditions depends both on the actual load current and the actual ambient temperature. It is therefore possible to operate at a current higher than the rated normal current when the ambient temperature is less than 40 °C, provided that the allowable temperature limit is not exceeded. Similarly, when the ambient temperature is higher than 40 °C, the current must be reduced to less than the rated normal current to keep the total temperature within the allowable limits.

The methods of calculating the allowable current under various conditions of ambient temperature and load are given in the subclauses 3.2.2.1 through 3.2.2.4. For some high ambient temperature conditions, it may not be practical to reduce the current sufficiently to keep the total temperatures within their allowable limits. Forced air cooling will help in many cases. Temperature limits of associated equipment such as cables and current transformers must be considered as this heat transfer is not taken into account during type testing. However no advice can be given for these cases or the similar effects of solar radiation which also must be considered.

3.2.2.2 Continuous load current capability based on actual ambient temperature

If the ambient temperature is above 40 °C, parts of the circuit breaker may exceed the specific limits given in Table 3 of IEC 62271-1, when carrying its rated normal current. In this case a higher rated normal current range for the switchgear has to be selected. For load currents which are lower than the rated normal current of the switchgear, a permissible maximum ambient temperature for that load current can be calculated with the help of Equation 1:

$$\theta_{a} = \theta_{max} - \left(\frac{I_{a}}{I_{r}}\right)^{1,8} \times (\theta_{max} - 40) \tag{1}$$

where

I_{a} = allowable continuous load current, in A, at actual ambient temperature θ_{a} (I_{a} is not to exceed two times I_{r});

I_{r} = rated normal current, in A;

θ_{max} = allowable hottest spot total temperature (θ_{max} = θ_{r} + 40), in °C;

θ_{r} = allowable hottest spot temperature rise at rated normal current, in K;

θ_{a} = allowable or actual ambient temperature, in °C.

NOTE The exponent would normally be 2, since the heat development in the switchgear and controlgear is proportional to the square of the current. Due to radiation and convection, the exponent may vary. Experience has shown that the exponent, depending on switchgear and controlgear design and components within the switchgear and controlgear, generally is in the range of 1,6 to 2,0. A value of 1,8 represents a compromise that covers most cases and is used in this application guide.

If Equation 1 is solved for the current I_{a} the allowable continuous load current at an actual ambient temperature θ_{a} can be calculated as given in Equation 2.

$$I_{a} = I_{r}\left(\frac{\theta_{max} - \theta_{a}}{\theta_{r}}\right)^{1/1,8} \tag{2}$$

The design features of switchgear and controlgear dictate the appropriate values of θ_{max} and θ_{r} to be used in the calculation. The major components of a circuit-breaker have several different temperature limitations which are specified in Table 3 of IEC 62271-1. The values for θ_{max} and θ_{r} should be determined as follows:

a) if the actual ambient temperature is less than 40 °C, the component with the highest specified values of allowable temperature limitations should be used for θ_{max} and θ_{r};

b) if the actual ambient temperature is greater than 40 °C, the component with the lowest specified values of allowable temperature limitations should be used for θ_{max} and θ_{r}.

The use of these values in the calculation will result in an allowable continuous current which will not cause the temperature of any part of the switchgear to exceed the permissible limits.

Example: A circuit breaker that has been tested for 3150 A rated normal current at an ambient temperature of 40°C will carry a maximum load current of 2500 A. What is the highest permissible ambient temperature?

As the estimated load current is less than rated current a higher ambient temperature is permissible. For the calculation θ_{max} and θ_r should be chosen as described under b).

In this case the lowest specified value in Table 3 of IEC 62271-1 is θ_{max} = 90 °C and θ_r = 50 K for the bare bolted connection in air. With Equation 1 the maximum permissible ambient temperature in this example is

$$\theta_a = \theta_{max} - \left(\frac{I_a}{I_r}\right)^{1,8} \times \left(\theta_{max} - 40\right) = 57 \ \ °C$$

3.2.2.3 Short-time load current capability

When switchgear and controlgear has been operating at a current level below its allowable continuous load current I_a, it is possible to increase the load current for a short time to a value greater than the allowable current without exceeding the permissible temperature limitations. There are different factors which influence the length of time period t_s of the overcurrent I_s. These are:

the magnitude of the current I_s itself;

the magnitude of the initial current I_i carried prior to the application of I_s;

the thermal time characteristic (thermal time constant) of the switchgear and controlgear;

the ambient temperature prior to and during application of overcurrent I_s.

The allowable duration of current I_s can be calculated directly by use of the Equation 3 and Equation 4:

$$t_s = \tau \left[-\ln \left\{ 1 - \frac{\theta_{max} - Y - \theta_a}{Y \left\langle (I_s / I_i)^{1,8} - 1 \right\rangle} \right\} \right] \qquad (3)$$

$$Y = (\theta_{max} - 40) \times \left(\frac{I_i}{I_r}\right)^{1,8} \qquad (4)$$

where

θ_{max} = allowable hottest spot total temperature (see Table 3, IEC 62271-1), in °C;

θ_a = actual ambient temperature in °C;

I_i = initial current carried prior to application of I_s, in A (maximum current carried by the circuit-breaker during the 4 hour period immediately preceding the application of current I_s);

I_s = short-time load current, in A;

I_r = rated normal current, in A;

τ = thermal time constant of circuit breaker, derived from temperature rise test in h;

t_s = permissible time for carrying current I_s at ambient θ_a after initial current I_i, time is given in the same unit as τ, h;

Y = a coefficient used for convenience, in K.

The time duration of the current I_s determined in this way will not cause the total temperature limits of the switchgear to be exceeded, provided that the following requirements are fulfilled:

a) the switchgear, and in particular the main contacts, shall have been well maintained and in essentially new condition;

b) the value used for current I_i is the maximum current carried by the switchgear during the 4 hour period immediately preceding the application of current I_s. To achieve the current value it is necessary to have a record of the current flow over the last 4 hours;

c) at the end of the period, the current I_s is reduced to a value which is not greater than the current I_a;

d) the value of current I_s is limited to a maximum value of two times rated normal current I_r. Otherwise actual overheating may occur as the heat from hot spots can not be distributed fast enough to colder regions.

NOTE If the temperature rise due to the load current I_s does not exceed θ_{max} the load current I_s is in an acceptable steady state. Thus the allowable time t_s is indefinite. Use of Equation 1 gives the information regarding the need, or otherwise, to apply Equation 3 and Equation 4.

Example: An SF_6 gas-insulated metal-enclosed switchgear with rated normal current carrying capability of I_r = 3150 A (having a temperature rise of 65 K at 3150 A) will carry a short-time load current I_s of 3600 A. Before application of the short-time load current the initial current I_i was 2500 A, the ambient temperature θ_a is 30 °C.

The highest total temperature θ_{max} = 115 °C is taken for bolted silver-coated connections in SF_6.The thermal time constant, derived from the type test, is 1,5 h. Generally, the time constant can be considered independent of the load and the temperature of the equipment.

With Equation 3 and Equation 4 the allowable time t_s is calculated to

$$t_s = 1{,}5\left[-\ln\left\{1 - \frac{115 - Y - 30}{Y\left\langle\left(\frac{3600}{2500}\right)^{1{,}8} - 1\right\rangle}\right\}\right] = 2{,}22\ \text{h}$$

from Equation 4:

$$Y = (115 - 40)(2500/3150)^{1{,}8} = 49{,}5\ \text{K}$$

After 2 h and 13 min the current has to be reduced to the maximum allowable current I_a which can be calculated with the help of Equation 2.

3.2.2.4 Influence of the altitude of switchgear and controlgear location

If the switchgear and controlgear relies on natural circulation of the ambient air and is located at an altitude between 2000 m and 4000 m, a check of the temperature rise measured during normal test at an altitude below 2000 m can be made in the following way:

The measured temperature rise at normal condition shall not exceed the temperature limits given in Table 3 of IEC 62271-1 reduced by 1 % for every 100 m in excess of 2000 m in altitude of the site of the installation.

NOTE This correction is generally unnecessary because the higher temperature rise at higher altitude due to the reduced cooling effect of the air is compensated by reduced maximum ambient temperature at altitude. (see Table 1 below). Consequently the final temperature is relatively unchanged at a given current.

Table 1 – Maximum ambient temperature versus altitude [2]

Altitude m	**Maximum ambient air temperature** °C
0 – 2000	40
2000 – 3000	30
3000 – 4000	25

3.3 Temperature rise testing

3.3.1 Influence of power frequency on temperature rise and temperature rise tests

A test performed at 60 Hz is considered to be valid for the same current rating with 50 Hz rated frequency.

In the case of open type switchgear and controlgear without ferrous parts adjacent to the current path a test performed at 50 Hz is also valid for 60 Hz provided that the temperature rise values recorded during the 50 Hz test do not exceed 95 % of maximum permissible values.

Caution is needed when tests performed at 50 Hz on switchgear and controlgear with ferrous parts are to be used to prove the performance of the switchgear and controlgear when rated for 60 Hz. The reason is that the ferrous parts adjacent to the current-carrying parts will have a frequency dependant heating effect due to the magnetic and eddy current losses. This will influence the temperature rise of the switchgear and controlgear.

Other examples of the frequency influence on the temperature rise are:

- single phase or three phase in one enclosure design;
- material of housing (insulator, metal);
- space between conductors and housing.

3.3.2 Test procedure

The test procedure, the test arrangement and the tolerances for current, frequency and ambient temperature are given and described in subclause 6.5 of IEC 62271-1. The duration of the test is determined by the time constant of the test object and the requirement to reach a stable value for the temperature rise. This condition is assumed to be satisfied when the increase of temperature rise does not exceed 1 K/h. This case will normally be met after a test duration of five times the thermal time constant of the test object. Care should be taken that this requirement is checked at the temperature rise values for each measurement point in relation to the ambient temperature (see Table 2). The change of the ambient temperature during the last quarter of the test period shall not exceed 1 K/h.

Table 2 - Some examples of different temperature rises related to the acceptance criteria for steady state conditions

Value	Example 1 $T(t) - T(t\text{-1h})$	Example 2 $T(t) - T(t\text{-1h})$	Example 3 $T(t) - T(t\text{-1h})$	Example 4 $T(t) - T(t\text{-1h})$
Maximum temperature rise during the last 1 h on the measurement points in K	45,0–43,2 = 1,8	51,0–50,5 = 0,5	53,0–51,9 = 1,1	62,3–61,5 = 0,8
Temperature rise of ambient temperature during the last 1 h in K	20,3–20,2 = 0,1	21,0–20,3 = 0,7	20,5–20,4 = 0,1	20,8–21,4 = - 0,6
Temperature rise of the measurement point related to the ambient temperature rise during last 1 h in K	1,8–0,1 = 1,7	0,5–0,7 = -0,2	1,1–0,1 = 1,0	0,8–(-0,6) = 1,4
Result	Steady state not reached	Steady state reached	Steady state reached	Steady state not reached

In Figure 2 the values are shown which have to be taken into account to check the steady state condition. At steady state the following equation must be fulfilled.

$$\Delta\theta_c\,(\text{over 1h}) - \Delta\theta_a\,(\text{over 1h}) < 1\text{K}$$

The values $\Delta\theta_c$ and $\Delta\theta_a$ are shown in Figure 3 which is an expansion of the relevant section of Figure 2. As mentioned above this condition will normally be reached after a test time of five times the time constant of the test object (see Figure 2).

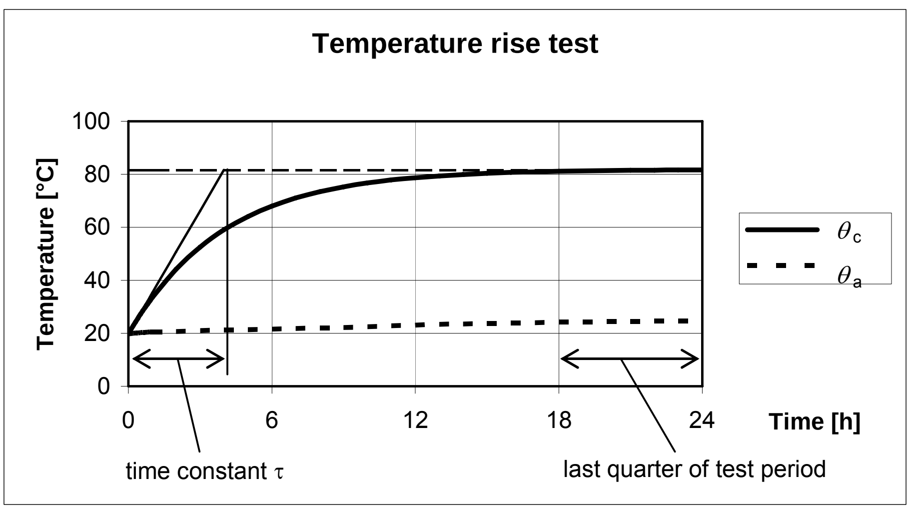

Figure 2 - Temperature curve and definitions

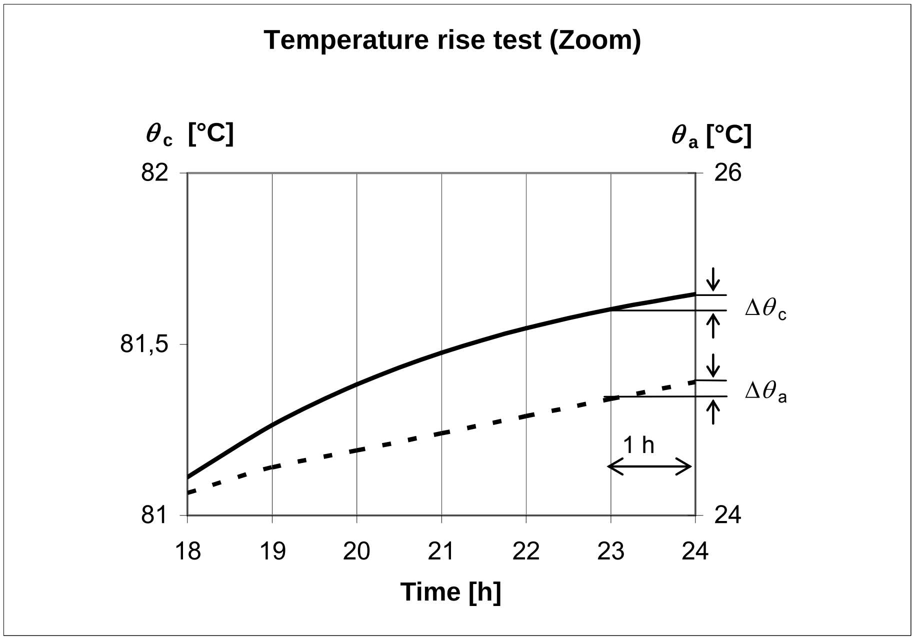

Figure 3 - Evaluation of the steady state condition for the last quarter of the test shown in Figure 2

3.3.3 Temperature rise test on vacuum circuit breakers

The temperature rise tests on vacuum circuit breakers are performed in the same manner as for other types of circuit-breakers and switchgear and controlgear. However, it is not possible to connect a thermometer or thermocouple to the main contacts of the interrupter unit. As stated in IEC 62271-1 the temperature at the terminals or connection parts of the vacuum bottle is taken as the qualifying measurement. The temperature rise of these parts shall not exceed the limits given in Table 3 of IEC 62271-1.

NOTE Because of the high vacuum in the bottle the heat can only be transferred by heat conduction over the connecting parts and by heat radiation. The contacts of the vacuum bottle can reach temperatures of up to 200 °C. This is not a concern, because the contacts are not exposed to degradation since they are in an oxygen-free environment. The load carrying capability of the contacts is not affected by these temperatures.

3.3.4 Resistance measurement

The procedure for measurement of the resistance of circuits is described in subclause 6.4 of IEC 62271-1.

3.4 Additional information

3.4.1 Table with ratios I_a/I_r

Table 3 - Ratios of I_a/I_r for various ambient temperatures based on Table 3 of IEC 62271-1

Maximum ambient temperature °C	Limiting temperature of different switchgear components									
	θ_{max}	70	80	90	100	105	115	120	130	155
	θ_r	30	40	50	60	65	75	80	90	115
60	*	0,54	0,68	0,75	0,79	0,81	0,84	0,85	0,86	0,89
50	*	0,79	0,85	0,88	0,90	0,91	0,92	0,92	0,93	0,95
40		1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
30	**	1,17	1,13	1,10	1,08	1,08	1,07	1,06	1,06	1,04
20	**	1,32	1,25	1,20	1,17	1,16	1,14	1,13	1,11	1,09
10	**	1,47	1,36	1,29	1,25	1,23	1,20	1,19	1,17	1,13
0	**	1,60	1,46	1,38	1,32	1,30	1,26	1,25	1,22	1,18
-10	**	1,72	1,56	1,46	1,40	1,37	1,32	1,30	1,27	1,22
-20	**	1,84	1,66	1,54	1,46	1,43	1,38	1,36	1,32	1,26
-30	**	1,95	1,75	1,62	1,53	1,50	1,44	1,41	1,37	1,30

θ_{max} = allowable hottest spot total temperature (θ_{max} = θ_r + 40), in °C.

θ_r = allowable hottest spot temperature rise at rated normal current, in K.

* for limiting current at this ambient temperatures, use lowest θ_{max} and θ_r

** for limiting current at this ambient temperatures, use highest θ_{max} and θ_r

3.4.2 Derivation of temperature rise equations

The temperature rise equations used for calculation of allowable time of a short time load current are derived in the following manner:

Let

θ_s = total temperature, in °C, that would be reached if current I_s were applied continuously at ambient θ_a;

θ_i = total temperature, in °C, due to continuous current I_i at ambient θ_a;

θ_t = total temperature, in °C, at some time t after current is raised from I_i to I_s.

Then

$$\theta_t = (\theta_s - \theta_i) \times \left(1 - e^{-t/\tau}\right) + \theta_i \tag{5}$$

Let $\theta_t = \theta_{max}$; solve for t.

Then

$$t_s = -\tau \ln\left[1 - \frac{\theta_{max} - \theta_i}{\theta_s - \theta_i}\right] \quad (6)$$

where

$$\theta_i = \left(\theta_{max} - 40\ {}^{o}C\right) \times \left(\frac{I_i}{I_r}\right)^{1,8} + \theta_a \quad (7)$$

and

$$\theta_s = \left(\theta_{max} - 40\ {}^{o}C\right) \times \left(\frac{I_s}{I_r}\right)^{1,8} + \theta_a \quad (8)$$

For the special case where the initial current is zero, the equations in this form are useful. By substitution and further manipulation, the equations given subclause 3.2.2.3 in terms of Y are obtained; these are convenient to use in the more usual case where the initial current is not zero.

3.5 References

[1] IEC 60059: IEC Standard current ratings

[2] IEC 60943, 1998: Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals

3.6 Bibliography

IEEE C37.010, 1999: Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

4 Insulation co-ordination

4.1 General

The IEC 62271-1 and IEC 62271-100 subclauses relevant to this chapter are:

4.2 Rated insulation level

6.2 Dielectric tests

7.1 Dielectric tests on the main circuit

8.102.6 Use at high altitudes

Insulation co-ordination is "the selection of the dielectric strength of an equipment in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices" (3.1 of IEC 60071-1).

Dealing with insulation co-ordination, it should be kept in mind the difference between "voltage surges" stressing the insulation in service, and "voltage impulses" used in conventional tests.

TC 28 has classified the different types of overvoltages that can appear in the system and related those to a standardised test voltage. This relationship is given in Table 1 of IEC 60071-1 and is repeated here for convenience (see Table 4).

The current insulating levels for switchgear and controlgear were prepared in 1971 by a joint working group with experts from CIGRE Study Committee A3 and from IEC Subcommittee 17A, when longitudinal and phase-to-phase insulations were not dealt with by the edition of IEC 60071-1 valid at that date. It was considered that the longitudinal insulation might have two very different purposes:

- the working function, that is the separation of two parts of a network;
- the safety function, to ensure that no voltage is applied on a part of the network where people might be working.

For that second function, it was considered that the dielectric withstand of the interrupting gap of a load switch or of a circuit-breaker was not reliable enough, due to its pollution by arc by-products, and it should be assumed by a disconnecting switch. In addition, with this latter device it was easy to increase the longitudinal insulation to provide a larger safety margin.

When an insulation co-ordination study is made in accordance with the process described in IEC 60071-1, all the electric stresses likely to occur at a given site and with a given probability are taken into account. This is done with respect to the insulation phase-to-earth, phase-to-phase and longitudinal stresses. These are classified according to their front duration whatever their origins. The influence of any voltage protective devices is also considered, see Table 1 of IEC 60071-1. Note that what is called "temporary" overvoltage includes the stresses generated at various frequencies, such as harmonics. The numerous correction factors are applied to each of them to take care of:

- performance criterion: the basis on which the insulation is selected so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will not cause damage to equipment insulation or affect continuity of service;
- statistical distribution: it is normally accepted to disregard those overvoltages which have a probability of occurrence less than 2 %;

- inaccuracy of input;
- effect of the equipment test assembly;
- dispersion in production;
- ageing in service: if not otherwise specified, an ageing factor of 15 % is considered for internal insulation and 5 % for external insulation;
- altitude correction.

To reduce the duration and the costs of the tests, only two types of test voltage shapes are in practical use. These are the power frequency and the standard lightning impulse voltages, for equipment up to and including 245 kV (Range I), and the standard switching and standard lightning impulse voltages, for equipment above 245 kV (Range II). For voltage range I the inherent switching surge strength (in p.u.) is higher than the magnitude of the surges at that voltage. In other words, the amount of insulation that is required to satisfy the lightning impulse and power frequency tests automatically exceed the requirements for the maximum switching surges that can occur on the system. Conversion factors are given in IEC 60071-2 so that "slow-front overvoltages" in range I or short-duration overvoltages of range II be covered by the selected test voltage shapes.

In using this approach, it follows that:

- no overvoltages larger than those used to assess the insulation levels are thought likely to occur on the incoming terminal of a switching device;
- a different probability uncertainty and performance criterion can be applied depending on whether they apply to the working function or to the safety function. By convention, it was decided that the insulation of the "isolating distance" (for the safety function) be the closest value to the IEC 60071-1 value but with a 15 % excess over the phase to earth insulation;[2][3]
- although no power frequency tests are required by IEC 60071-1 for range II it can be agreed that product standards may add them when necessary, which is the case with switchgear and controlgear, due to their elaborated design, and because it is a convenient voltage shape for routine tests (IEC 60071-1 deals only with type tests and does not consider the safety aspects).

There are some differences between the insulation levels stated in IEC 60071-1 and those in IEC 62271-1:

- not all of the insulation levels of IEC 60071-1 are taken into IEC 62271-1. This is because the first standard is designed for every type of equipment and some of its values are not used in the latter for switchgear;
- the switching impulse withstand voltage of longitudinal insulating is lower in IEC 62271-1. It should be noted that there are only two cases where longitudinal insulation stress occurs:
    - when a line crosses another line or a busbar;
    - and the case of switchgear and controlgear.

  In the first case, it is easy and economic to use longer clearances; it is more difficult to increase the longitudinal insulation of switchgear and controlgear, and not really necessary, as explained in Appendix A to this chapter. In fact, the insulation levels specified in IEC 62271-1 have been used successfully for twenty years or so, and IEC TC 28, responsible of IEC 60071, agreed that switchgear standards keep their values (see minutes of meeting RM 3606/TC 28)

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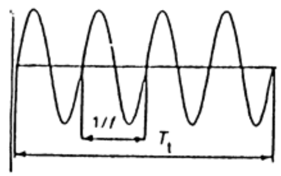
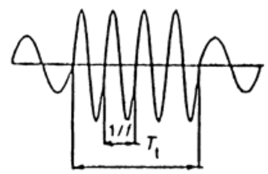
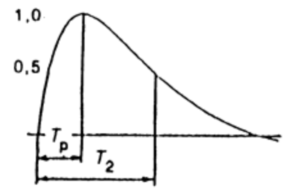
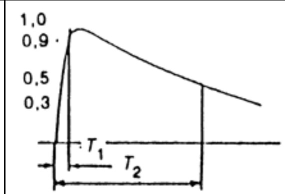
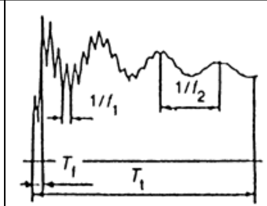
2 Nevertheless, the only safe condition to work on a network is to earth it on each side of the work site.

3 "Self-coordination", which would mean that the withstand level of the longitudinal insulation is always higher than the disruptive level phase-to-earth, is unrealistic because it is impossible to realise it on the same test specimen in both polarities and for all possible voltage wave shapes.

The splitting into two voltage ranges is done mainly in consideration of neutral earthing systems: in range II, it is considered usual that the neutrals are solidly earthed. Therefore, the voltage stresses are lower. This explains why the same lightning withstand voltage is required for 245 kV and for 300 kV.

Background information on insulation levels and associated testing is provided in Appendix A.

Table 4 – Classes and shapes of stressing voltages and overvoltages (from IEC 60071-1)

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast front
Voltage shape					
Range of voltage shapes	f = 50 Hz or 60 Hz $T_t \geq$ 3 600 s	10 Hz < f < 500 Hz 3 600 s $\geq T_t \geq$ 0,03 s	5 000 μs $\geq T_p >$ 20 μs $T_2 \leq$ 20 ms	20 μs $\geq T_1 >$ 0,1 μs $T_2 \leq$ 300 μs	100 ns $\geq T_f >$ 3ns 0,3 MHz > f_1 < 100 MHz 30 kHz < f_2 < 300 kHz $T_t \leq$ 3 ms
Standard voltage shape	f = 50 Hz or 60 Hz T_t *)	48 Hz $\leq f \leq$ 62 Hz T_t = 60 s	T_p = 250 μs T_2 = 2 500 μs	T_1 = 1,2 μs T_2 = 50 μs	*)
Standard withstand test	*)	Short-duration power frequency test	Switching impulse test	Lightning impulse test	*)

*) To be specified by the relevant apparatus committees.

4.2 Longitudinal voltage stresses

4.2.1 General

Normally a circuit-breaker does not have a disconnecting function, this is the duty of the disconnector.

For its working function, it has firstly to withstand the recovery voltage after having extinguished the arc. In the open position it may be stressed by the power frequency voltage on one terminal with the other stressed by any of the following voltages:

- the D.C voltage resulting from the trapped charge of the overhead line in the case of no-load line or capacitor bank switching;
- power frequency voltage in out-of-phase condition, in the case when busbars or generators are switched;
- a slow-front surge in the case of a switching operation at the remote end;
- a possible fast front surge in the case of a lightning stroke.

When the circuit is not in use, the circuit-breaker is normally insulated by a disconnector and may be stressed only for a short period. It is not the case for bus tie (busbar) couplers, but the two bus voltages rarely have a large phase shift. Exposed situations where complete out-of-phase voltages will be present for minutes do exist, e.g. in the case of circuit-breakers used for synchronisation purposes, sometimes with a higher component on the generator side.

4.3 High-voltage tests

4.3.1 Type-tests

The standard dealing with high-voltage insulation tests is IEC 60060-1, but the various types and values of dielectric tests are specified in IEC 60071-1, because their statistical meaning is to be taken into account in the process of designing insulation co-ordination. It must be kept in mind that each test voltage shape is a conventional shape to evaluate the behaviour of the insulation when stressed by various voltage stresses, short duration, slow-front or fast front (see Table 1 of IEC 60071-1).

Ideally, the best would be to use a test procedure providing some statistical results. To do that, it is necessary to have an idea of the limit and therefore to have at least one disruptive discharge. But if the test object includes a non-self restoring part in its insulation system, to reach the limit would mean some destructive effect. In many cases, the insulation is composed of self-restoring parts and of non-self-restoring mixed together. Therefore, several procedures are proposed, supposedly having the same severity, which means that the probability that a "good" specimen is rejected (risk of the manufacturer) is the same as a "bad specimen" being accepted (risk of the user):

- for complete self restoring insulation (air at atmospheric pressure associated with glass or porcelain), the "up and down" procedure provides the U_{50} value, the critical disruptive level, and an estimate of the standard deviation. It is called "procedure D" in IEC 60060-1;
- for clearly defined non self-restoring insulation, "procedure A" of the same standard assess an assumed withstand voltage (three shots without disruptive discharge);
- for insulation systems composed of mixed self-restoring and non self-restoring insulation, a compromise was found with procedures B or C, where no disruptive discharges are allowed on the non self-restoring part of the insulation. Subclause 5.3.4 of IEC 60071-2 shows how procedure B and C give the same probability to pass a test at 90 % of the maximum withstand value. This is with a much better selectivity with procedure B. The question most likely to be raised in the laboratory occurs when the last (or last two) applications of the test voltage leads to disruptive discharges, and whether they are on

self-restoring insulation or not. For this reason IEC 62271-100 requires 5 non-disruptive to conclude the test. This is aimed at giving confidence that the non self-restoring insulation is likely to be sound.

Another problem may exist when applying atmospheric correction factors for external insulation in the case that the insulation system of the switchgear and controlgear consists of internal and external insulation in parallel. Subclause 11.4 of IEC 60060-1 gives some guidance on how to perform the tests.

The following additional concerns may exist:

- the test voltage across longitudinal insulation or phase-to-phase is higher than the test voltage phase-to-earth. Procedures for those cases are given in 6.2.5.2 of IEC 62271-1;
- three-phase switchgear and controlgear in the same enclosure: test voltages are usually applied between phase and earth, across longitudinal insulation of each pole and phase to phase separately.

4.3.2 Routine tests

It should be noted that these are detailed in the relevant standards. The power frequency test is used because it is most suitable for factory conditions.

4.4 Correction factors

4.4.1 Altitude correction factor

In the determination of the required withstand voltages, a number of factors have to be taken into account: the atmospheric correction factor k_{at} and a safety factor k_s.

An effect of altitude is the reduction of the atmospheric pressure. A reduced atmospheric pressure reduces the disruptive voltage of a given gap in air. Subclause 4.2.2 of IEC 60071-2 provides equations for derating insulation levels according to the voltage shape and to the electrode configurations based on measurements made in HV laboratories. The difficulty occurs when it comes to switching surges. So, in IEC 62271-1, it was proposed and accepted to simplify the altitude correction factor as shown in Figure 1 of this standard. In addition, these equations are general for any altitude above sea level. But in the process of assessing insulation level in IEC 60071-1, a correction is already included to cover use up to 1000 m. As a consequence, the insulation levels stated in IEC 62271-1 are valid up to 1000 m and, for higher altitudes, the equation for the correction factor is modified accordingly.

The altitude correction is applicable to external insulation only and is incorporated into the atmospheric correction factor, since the air density is a function of the altitude. The dielectric strength is dependent on the air density. The altitude dependence on the atmospheric pressure is given in IEC 60721-2-3 in tabular form. IEC TC 28 (Insulation coordination) has transferred the information given in IEC 60721-2-3 into Equation 9 that deviates by no more than 1 % from the information given in IEC 70721-2-3:

$$\frac{b_0}{b} = e^{H/8150} \qquad (9)$$

where

b_0 standard barometric pressure, 101,3 kPa (or 1013 mbar)

b pressure at altitude H above sea level (Pa)

H altitude above sea level (m)

The air density correction factor is given as (IEC 60060-1):

$$k_d = \delta^m \quad (10),$$

with $\delta = \frac{b}{b_0} \times \frac{273 + t_0}{273 + t}$

where,

k_d is the air density correction factor

δ is the air density

t_0 is the standard reference temperature, 20 °C

m is an exponent dependent on the minimum discharge path and other attributes. Values of m can be derived from Figure 4 of IEC 60060-1. These values are based on measurements performed at altitudes up to 2000 m.

The fixed (and conservative) values for m are given for convenience, more detailed values are given in IEC 60071-2. The values are reproduced here from IEC 62271-1 (see Table 5):

Table 5 – Values for *m* for the different voltage waveshapes

m	Power frequency	Switching impulse	Lightning impulse
Phase-to-earth	1	0,75	1
Phase-to-phase	1	1	1
Longitudinal	1	0,9	1

Combining Equations (9) and (10) and assuming standard reference temperature applies, the following equation is obtained for the altitude correction factor:

$$k_{alt} = e^{m\left(\frac{H}{8150}\right)} \quad (11)$$

Subclause 2.2.1 of IEC 62271-1 specifies the following altitude correction factor:

a) altitudes up to and including 1000 m: $k_{alt} = 1$

b) altitudes higher than 1000 m: $k_{alt} = e^{m(\frac{H-1000}{8150})}$ (12)

where

k_{alt} is the altitude correction factor;

H is the altitude in m above sea level;

m is an exponent.

The specification of the altitude correction factor as given in IEC 62271-1 has been based on the following considerations.

The safety factors used are k_s = 1,05 for external insulation and k_s = 1,15 for internal insulation.

Considering the overall correction k_{total} = (k_{at} × k_s) as a function of the altitude at constant humidity and temperature, assuming m = 1, the following can be determined:

External insulation: at 0 m k_{total} = 1,05 and at 1000 m k_{total} = 1,19

Internal insulation: k_t = 1,15 (independent of altitude)

For a circuit-breaker having internal and external insulation in parallel (which is frequently the case), the overall correction factors are nearly equal at 1000 m. This means that the safety factor of 1,15 covers the requirements for both internal and external insulation up to an altitude of 1000 m.

As the safety factor is included in the required withstand voltages, these voltages are valid up to and including 1000 m.

4.4.1.1 Examples of application of the altitude correction factor

Example 1: A 245 kV circuit-breaker is going to be installed in a substation at an altitude of 1800 m above sea level. The user specification for the insulation level is 1050 kV at site level. Which circuit-breaker will fulfil these requirements?

The required insulation level at standard atmospheric conditions (sea level) will be obtained applying the altitude correction factor (Equation (12)) and the following considerations:

- For lightning impulse and power frequency m = 1, hence k_{alt} = 1,103. This means that the circuit-breaker needs to be tested at sea level with a voltage of 1050 × k_{alt} = 1158 kV.
- The nearest standardized impulse voltage is 1175 kV, which belongs to a system voltage of 362 kV.
- The requirement for the power frequency withstand at sea level is 507 kV (dry and wet). Regarding the test to earth this is not fully covered by the requirements for a 362 kV circuit-breaker. However, a 362 kV circuit-breaker has been tested with switching impulse (dry and wet), which gives higher stresses on the external insulation compared to the power frequency test, hence one can safely assume that a 362 kV circuit-breaker fulfils the requirements of a 245 kV circuit-breaker used at 1800 m above sea level.

Conclusion: The 245 kV circuit-breaker fulfilling the requirements for an altitude of 1800 m will be a circuit-breaker having an insulation level belonging to a system voltage of 362 kV.

Example 2: A 245 kV circuit-breaker is tested in a testing station that is located at an altitude of 800 m above sea level. What are the correct test values?

Test values and conditions for testing of switchgear and controlgear is referring to standard atmospheric conditions. As the testing station is located at 800 m above sea level, the test values for external insulation need to be corrected to the standard atmospheric conditions. Applying Equation (11) using H = 800 and m = 1 gives k_{alt} = 1,103.

The test values for external insulation in the testing station may be reduced to 1050/k_{alt} = 952 kV_{peak} for the lightning impulse withstand test and 417 kV r.m.s. for the power frequency test, providing the circuit-breaker has external insulation only. When the circuit-breaker has both internal and external insulation, k_{alt} = 1.

Example 3: The circuit-breaker of Example 2 is tested in the same testing station at an altitude of 800 m for application at an altitude of 1800 m. What is the correct test voltage?

The testing values at sea level have been derived in Example 1 and are 1158 kV for the lightning impulse withstand test and 507 kV r.m.s. for the power frequency withstand test.

Application of Equation (11) (calculated in Example 2) to these values give the following result:

- Lightning impulse withstand test: 1050 kV_{peak};
- Power frequency withstand test: 460 kV.

Again, this is only valid for the external insulation of the circuit-breaker.

4.4.2 Humidity correction factor

IEC 62271-1 deviates from IEC 60060-1 with respect to the humidity correction factor h to be applied during dry tests of MV switchgear.

In fact, the correction factors as defined in IEC 60060-1 does not fully apply to MV switchgear in which dielectric stress implies short distances and highly stressed insulating surfaces, and where dielectric failure location and distance are practically impossible to define. The failure mode depends on temperature and humidity as shown in Figure 4.

- in area 3 and 4, the external insulation behaves as an air gap;
- in area 2, due to high absolute moisture content, it is observed that flashovers generally occur along the insulating surface and cannot be considered as if in air. This can be explained by the fact that contrary to an air gap, the withstand voltage along an insulating surface tends to decrease when humidity increases. So, in case of high moisture content, the weakest point may become the surface instead of the air gap;
- the cases corresponding to area 1 practically do not exist except for the zone near the standard conditions.

In order to avoid varying interpretations and have a practical approach for laboratories, a simplified method to determine w values is preferred to the calculation as given in IEC 60060-1. It was based on the experience of the first edition of IEC 62271-1 in which the factor w value equal to 1 had been used for long time by laboratories with satisfactory results especially in the area 3 of the curve ($h \leq 11$ g/m^3), and on recent results in the area 2 ($h > 11$ g/m^3) showing that taking $w = 0$ gives good correlation with experimental data.

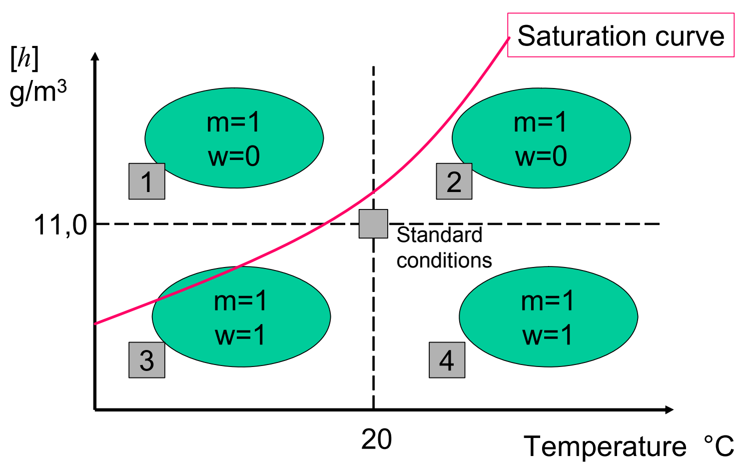


Figure 4 – Failure mode of external insulation of MV switchgear

Appendix A

Background information about insulation levels and tests

A.1 Specification

The rated insulation levels are mainly based on the requirements of IEC 60071-1. The application guide IEC 60071-2 explains the relationship between the nominal system voltage and the standardized insulation levels. However, these standards are intended to be applied to all types of equipment: insulators, cables, power transformers, etc. Therefore, some related considerations need to be addressed in applying them to high-voltage switchgear and controlgear.

A.1.1 Phase-to-earth

The insulation levels have been selected taking into account the values most commonly used for switchgear and controlgear.

In addition to IEC 60071-1, a rated short-duration power-frequency withstand voltage is required for rated voltages higher than 245 kV, in order to verify internal insulation voltage withstand capability with respect to temporary overvoltages.

A.1.2 Phase-to-phase

No changes are made to the specifications of IEC 60071-1 for the insulation between poles.

A.1.3 Longitudinal insulation

Since no other IEC product standards specify longitudinal insulation, the rated withstand values do not need be taken from IEC 60071-1.

A.1.3.1 Isolating distance

In addition to the requirements of insulation coordination, the standard specifies insulation of the “isolating distance”. This is to cover special conditions which are to be met by disconnectors to provide an additional safety factor (1,15) (see 5.102 of IEC 62271-102).

The intent is not to provide “auto-coordination” which would require that any disruptive discharge occurs phase-to-earth on the switching device rather than between its open contacts. It is generally recognized that when work has to be carried out on a high-voltage conductor, safety is assured only when the conductor is directly connected to earth. Local safety rules shall apply.

A.3.1.2 Combined voltage tests

A combined voltage test is one in which two separate sources, generating voltages against earth, are connected to two terminals of the test object (see Clause 26 of IEC 60060-1 and Tables 2a and 2b of IEC 62271-1).

Such tests are required for switchgear and controlgear of 300 kV and above to demonstrate longitudinal voltage withstand capability. They may also be useful for testing where the test voltage between two live parts is specified to be higher than the phase-to-earth value.

The components of the combined voltage tests have been specified based on the following considerations:

a) Short-duration power-frequency withstand voltage

The specified power-frequency withstand voltage values correspond to the most severe situation of full load rejection after disconnection of a generator at full load. The overvoltage on the generator side of the switching device may reach up to 1,5 times the system voltage and may last up to 3 s with a possible phase shift. At the same time, the network side of the switching device is energized at the normal operating voltage. The sum of the two voltages in phase opposition is 2,5 times the system voltage, extended here to 2,5 the rated voltage.

b) Switching impulse withstand voltage

The switching impulse voltage value specified phase to earth in Column 4 of Table 2 is designed to cover the highest slow-front overvoltage likely to occur at the switching device terminal. This occurs at the remote end of a line after fast reclosing from the other end on a trapped charge. This highest overvoltage is of the same polarity as the power-frequency voltage of the network at this instant and therefore is not to be used when the maximum stress across a switching device is the consideration. The maximum longitudinal stress takes place when an overvoltage occurs on the polarity opposite to the power-frequency voltage of the system. The maximum value for this case occurs on closing from the remote end and is lower than the value occurring on reclosing. Therefore, the values of switching impulse specified in Column 6 are lower than those of Column 4.

c) Lightning impulse

In the process of designing insulation coordination, IEC 60071-1 takes into account the probability of occurrence of a particular event in order to determine the performance criteria. The likelihood that the maximum fast-front overvoltage occurs on the terminal of a switching device at the instant when its opposite terminal is energized with the maximum system voltage at opposite polarity is small. Therefore, the specified lightning impulse to be considered in this particular case need not be as high as for the general case. A reduction of about 5 % has proved to be more than adequate during the last decades. For convenience of testing, this reduction of the total voltage across the switching device is applied to the power-frequency voltage component.

A.2 Testing

A.2.1 Test of the longitudinal insulation with the alternative method

To be strictly comply with the preferred method, the voltage between the energized terminal and the base frame should be equal to the rated withstand voltage phase to earth. But it is difficult to adjust exactly this voltage simultaneously with the longitudinal test voltage. The value of U_f has been fixed considering the following facts:

- the test voltage between any terminal and the base frame cannot exceed the rated phase to earth withstand voltage without risk;
- the electric field stress across open contacts is mainly dependant on the voltage across them, and to a lesser extent on the voltage to earth;
- the determination of the rated withstand voltage of the isolating distance is not that accurate;
- a safety factor is included in the process of insulation coordination (see IEC 60071-1) to account for such testing difficulties.

A.2.2 Test between phases for rated voltages above 245 kV

A.2.2.1 Voltage sharing between the two switching impulse components of the phase-to-phase test

The actual ratio of the two components may have any value on the network. In order to simplify the tests IEC 60071-1 decided to specify balanced components (same amplitude with opposite polarities). Since this leads to a less severe condition, the total test voltage was increased to cover any realistic case (see Annex A of IEC 60071-2). Therefore, if the same total test voltage is applied by an unbalanced sharing of the components, the test is more difficult than required.

In reality few laboratories have two impulse generators and the peak of a power-frequency voltage may replace one component. However, this leads to power-frequency voltages higher than specified phase-to-earth and for a rather long duration. Therefore, some compromise is necessary depending on the actual phase-to-earth withstand voltage of the switching device and on the facilities of the laboratory.

A.2.2.2 Wet tests

No wet switching impulse tests are normally necessary between phases for the following reasons:

- enclosed insulation does not need wet tests;
- insulation between phases exposed to weather precipitations is only atmospheric air and is not sensitive to this influence for switchgear and controlgear of rated voltage above 245 kV.

A.2.3 Combined voltage tests of longitudinal insulation

A.2.3.1 Tolerance on the power-frequency voltage component

According to IEC 60060-1, the tolerance of the power-frequency component voltage should be maintained within 3 % of the specified level. This allows for some variations from the main voltage without permanent adjustment. During a combined voltage test, however, the laboratory has also to monitor many other parameters from the impulse voltage source. Therefore a higher tolerance is acceptable for this component with the understanding that the test voltage to be considered is the actual total voltage across the open contacts or the isolating distance.

A.2.3.2 Atmospheric correction factor

The atmospheric correction factor should be calculated according to IEC 60060-1. In the case of combined voltage tests, the atmospheric correction factor should be applied to the total test voltage, i.e. the sum of the two components.

5 Impulse voltage withstand test procedures

The IEC 62271-1 and IEC 62271-100 subclauses relevant to this chapter are:

6.2.4 Criteria to pass the test

6.2.5 Application of the test voltage and test conditions

6.2.6.2 Lightning impulse voltage tests

6.2.7.2 Switching impulse voltage tests

6.2.7 Lightning impulse voltage tests

5.1 Introduction

The purpose of this chapter is to explain the basis for the several impulse voltage withstand test methods used to verify the insulation integrity of high voltage switching devices.

In 6.2.5 of IEC 62271-1 the application of the test voltage and test conditions are given. This subclause prescribes several test series, such as testing across the open switching device, to earth, and between phases, as well as tests with power frequency and impulses with positive and negative voltage polarity. Each of these test series has to be considered individually as each of them has to show that the individual insulation under test meets the particular requirements. According to the philosophy of insulation coordination these requirements are based on a maximum flashover probability of about 10 %. This should be met by each individual insulation, as well as by the whole switching device. Consequently, adding up all tests performed on the switching device is not justified and does not give any information on the withstand probability of the whole device.

5.2 Application to high voltage switching devices

For impulse tests, the following two procedures are given in 6.2.4 of IEC 60694:

Procedure B of IEC 60060-1: 15 consecutive impulses at the rated lightning or switching impulses at the rated withstand voltage for each test condition and each polarity. The test object is considered to have passed the test if the number of disruptive discharges (flashovers) on the self-restoring part of the insulation does not exceed two for each series of 15 impulses and if no disruptive discharge occurs on non-self-restoring insulation. This method is referred to as the 15/2 method.

As an alternative, Procedure C of IEC 60060-1 may be applied. In this case the test consists of three consecutive impulses for each test condition and each polarity. The test has been passed if no disruptive discharge occurs. If one disruptive discharge (flashover) occurs on the self-restoring part of the insulation, then 9 additional impulses may be applied. If no disruptive discharge occurs during these additional impulses the test object is considered to have passed the test. This test procedure is referred to as the 3/9 method.

Both impulse test procedures have been applied worldwide for many decades and have proven to be valid to determine whether a circuit-breaker or switchgear design is correct.

5.3 Additional criteria to pass the tests

5.3.1 Procedure B

Based on the 15/2 method, IEC 62271-100 contains additional criteria to pass the tests. If disruptive discharges occur during the application of 15 test impulses it shall be demonstrated that they did not occur on non-self-restoring insulation (SF_6 gas is considered self-restoring). Evidence that damage has not occurred to non-self restoring insulation can be confirmed by five consecutive impulse withstands following the last disruptive discharge. If permissible disruptive discharges occur within the last five test impulses sufficient additional verification impulses may be applied in order to achieve five consecutive withstands.

The led to the modified 15/2 series (designated as 15/2M) whereby the last occurring acceptable flashover must be followed by five withstands. Thus, if the tenth test impulse resulted in a disruptive discharge and the next five test impulses were withstands, then the test is successful; however, if the fifteenth test impulse resulted in disruptive discharge, then for the test to be successful five additional test impulses (verification impulses) must be applied and all must be withstands.

A variation of the 15/2M method is to permit one disruptive discharge in the verification impulses. That disruptive discharge has to be followed by five withstands, thus allowing up to three disruptive discharges in total. This method is designated as 15/2MPLUS. The 15/2MPLUS method would increase the maximum number of test impulses to 25 for the case where the last of five verification impulses is a disruptive discharge. A further variation, designated 15/2MF, permits one flashover during the verification impulses but still retains the maximum limit of two disruptive discharges.

5.3.2 Procedure C

The original test method required in ANSI/IEEE C.37.09 was the so-called 3/3 method. Three test impulses are applied with the following possibilities:

- all three impulses are withstands, then the test is successful and complete;
- if one disruptive discharge occurs, then three further impulses are applied and all must be withstands for the test to be successful;
- if two disruptive discharges occur, the test is a failure.

This method was later modified to the 3/9 method described in 5.2 which simply means a disruptive discharge in the application of the first three impulses shall be followed by 9 withstands.

5.4 Additional considerations

The purpose of type testing is to demonstrate that the test object meets the requirements. If it does not pass the test, the reason has to be shown, and exactly what has to be improved or changed to justify the repetition of the test. For the new test, a new test object should be submitted which can be an improved device. One should not use the same test object or a second one of its kind in the expectation of success in a second or third attempt.

Following this philosophy, as a rule even a 10 % flashover probability is considered too high. Calculation shows that for a design with a probability of flashover of 5 %, the 15/2MF test will have a probability of rejection ($1-P_a$) of 5,15 %, and the 3/9 test a probability of rejection of 5,73 %. Based on these values, Procedures B and C are considered statistically equivalent for switchgear type testing.

5.5 Detailed analysis of the different test methods

Appendix A describes the statistical sampling plans on which the various test methods are based.

Appendix B gives the probability equations applicable to the various test methods.

Appendix C contains a summary of the various test methods and their attributes.

Appendix A

Statistical background

A.1 Theory

Originally invented to test insulators, and described in IEC 60060-1, the statistical considerations from which the impulse voltage withstand test procedures were derived actually apply to batches (or lots), i.e. to testing of a relatively large number of samples. Therefore, they are suited in a limited way, only, to prove the quality of individual items, such as switchgear.

Nevertheless, as the procedures have been generally accepted for impulse voltage withstand testing of high voltage switchgear it may be justified to present their mathematical background.

A.1.1 Additive probabilities

According to one axiom of probability the probability function for mutually exclusive events is additive [1]. For example the probability of event A or event B is the sum of their individual respective probabilities providing the two events are mutually exclusive.

A.1.2 Special law of multiplication

According to the special law of multiplication the probability that a number of independent events will all occur is the product of their individual respective probabilities [1]. For example the probability of event A and event B is the product of their individual respective probabilities providing the two events are independent.

A.1.3 Binomial distribution

The relative merit of the individual plans is analyzed by means of the binominal probability distribution and two other relations from probability theory. However, the probability theory has a limited applicability when the number of samples is small or, in the extreme case, when this number is down to one. Yet, this analysis may be useful to understand the background of the test procedures defined in IEC 60060-1 and 6.2.4 of IEC 60694 and IEC 62271-100.

Impulse tests are statistically a set of repeated trials. Letting "n" represent the number of trials and "r" the number of test failures, the tests can be analyzed using the binominal probability distribution on the basis that the following assumptions apply [1]:

a) There are only two possible outcomes for each trial, "success" or "failure". (Textbooks usually assign the outcome associated with "r" as a success, without inferring that success is necessarily a desirable outcome. In our particular case we are designating the outcome associated with "r" a failure because in the context of dielectric testing a disruptive discharge is a failure.);

b) The probability of failure is constant from trial to trial and is denoted as "p"; the probability of success is thus $(1 - p)$;

c) There are "n" trials, where "n" is a given constant;

d) The "n" trials are independent.

The probability of r failures in n trials for a probability of failure p is given by:

$$b(r; n, p) = \binom{n}{r} p^r (1-p)^{n-r} \qquad (13)$$

where $\binom{n}{r} = \frac{n!}{r!(n-r)!}$

It follows from the axiom described above that the cumulative probability of r or fewer failures in n trials is:

$$B(r; n, p) = \sum_{r=0}^{r} \binom{n}{r} p^r (1-p)^{n-r} \qquad (14)$$

$B(r,n,p)$ is the probability of acceptance of the test based on a single sampling plan where a maximum of r failures are allowed.

In the case of sampling schemes consisting of more than one sampling plan the cumulative probability distributions for the respective plans are combined in accordance with the axiom and law described above to yield the probability of acceptance for various values of "p" using that scheme.

P_a will be denoted the probability of acceptance using a particular sampling scheme.

The equations for P_a for all the series are given in Appendix B.

To illustrate the application of the theory, the 3/9 method is considered. The acceptable outcomes are 3/0 or (3/1 and 9/0):

$$P_a = \binom{3}{0} p^0 (1-p)^{3-0} + \left[\binom{3}{1} p^1 (1-p)^{3-1} \times \binom{9}{0} p^0 (1-p)^{9-0} \right]$$

$$= \frac{3!}{0!(3-0)!}(1-p)^3 + \left[\frac{3!}{1!(3-1)!} p(1-p)^2 \times \frac{9!}{0!(9-0)!}(1-p)^9 \right]$$

$$= (1-p)^3 + 3p(1-p)^{11}$$

The plot of P_a as a function of "p" is usually called an operating characteristic curve.

While the 15/2 method has three acceptable outcomes, the 15/2M method is more complex having 23 acceptable outcomes.

The 15/2MPLUS method has 93 acceptable outcomes, the 23 outcomes as for the 15/2M method plus an additional 70 outcomes due to now allowing one disruptive discharge in the verification impulses.

The 15/2MF method has 38 acceptable outcomes, the 23 outcomes as for the 15/2M method plus an additional 15 outcomes due to allowing one disruptive discharge in the verification impulses where only one disruptive discharge has occurred during the 15 test impulses.

The operating characteristic curves for the various methods are plotted in Figure A.1 and Figure A.2 based on the equations in Appendix B.

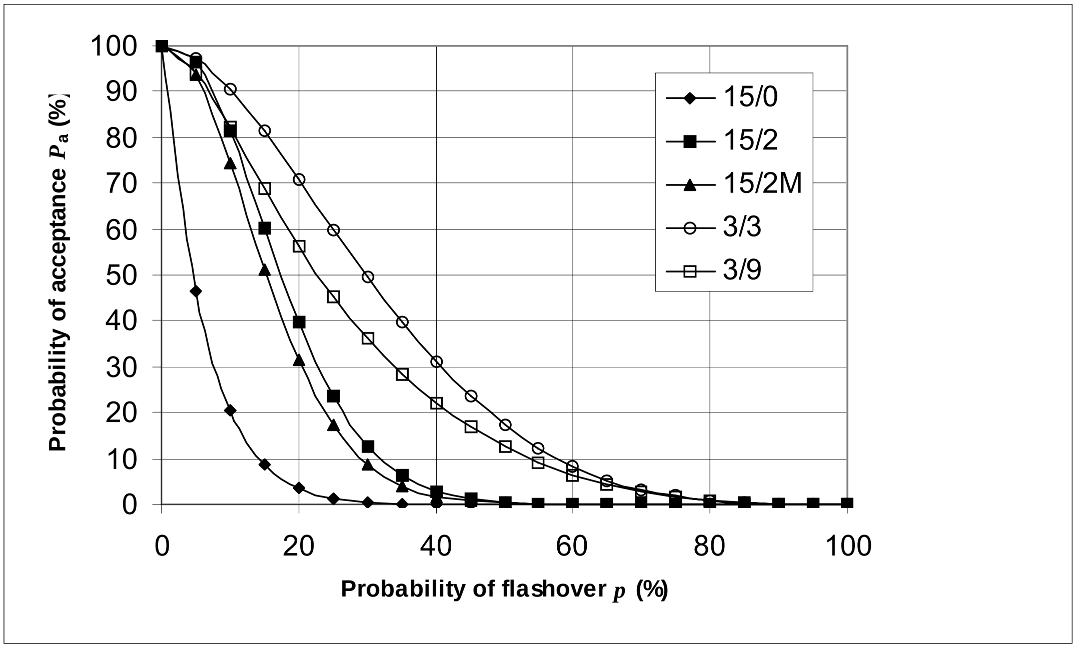


Figure A.1 - Operating characteristic curves for 15/0, 15/2, 15/2M, 3/3 and 3/9 test series

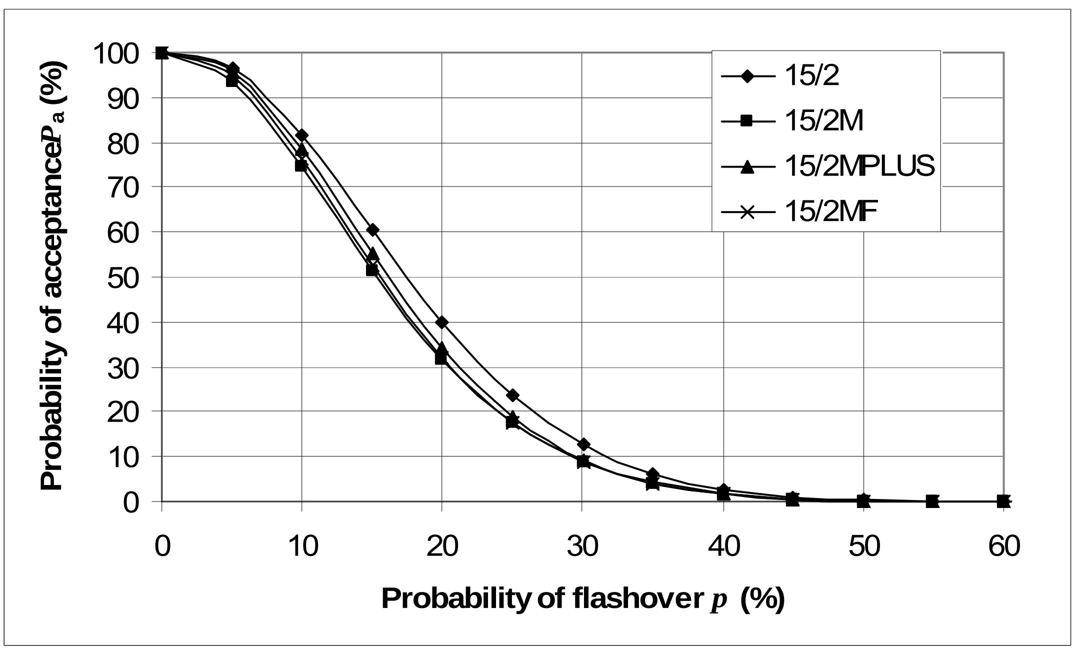


Figure A.2 - Operating characteristic curves for 15/2, 15/2M, 15/2MPLUS and 15/2MF test series

A.2 Comparison

The various test methods are actually statistical sampling plans developed to distinguish between "good" and "bad" products out of a larger number of samples, the 15/2 method being a single sampling plan and the 3/3 and 3/9 method being double sampling plans. The 15/2M, 15/2MPLUS and 15/2MF methods can be described as multiple sampling plans. A test method consisting of more than one sampling plan is often called a sampling scheme. The notion of sampling implies risk: the manufacturer's risk is that a "good" product will be rejected (fails the test) and the risk of the user is that a "bad" product will be accepted (passes the test). In reality both risks are mitigated by design safety margins and the ultimate question is which plan gives the best product quality.

To make a comparison between the different methods, two quantities need to be defined (again, it must be remembered that these considerations apply to a large number of samples and not to testing of an individual test object).

A.2.1 Manufacturer's risk (α risk)

The manufacturer's risk is the probability that a "good" lot will be rejected by the sampling plan. This risk is usually set at 5 % (corresponds to 95 % acceptance) and is stated in conjunction with a numerical definition of "good" quality such as an Acceptable Quality Level (AQL). Ideally the AQL is the value of "p" corresponding to a value of P_{a} equal to 95 %. The AQL is thus the maximum percent defective that, for the purpose of sampling inspection (testing in this case), can be considered satisfactory as a process average.

A.2.2 User's risk (β risk)

The user's risk is the probability that a "bad" lot will be accepted by the sampling plan and is stated in conjunction with a numerical definition of "bad" quality such as a Lot Tolerance Percent Defective (LTPD). In quality assurance procedures, when checking and selecting the acceptable samples out of a lot, a user's risk of 10 % is common and LTPD is the lot quality (i.e. value of "p") for which there is a 10 % probability of acceptance, i.e. 10 % of such lots will be accepted.

The α and β risks for the operating characteristic curves of Figure A.1 and Figure A.2 are summarized in Appendix C.

Another measure for comparison of sampling plans is to consider how well the plans discriminate between "good" and "bad" lots. An ideal plan would discriminate absolutely between the "good" and "bad" lots as is shown in Figure A.3 for an AQL of 10 %; all lots to the left of the vertical acceptance line will be accepted and those to the right will be rejected. The closer the actual sampling plan comes to the ideal plan, the better its discrimination.

To have a similar probability of acceptance as the 15/2 test procedure at the 10 % probability of flashover (AQL), the 3/3 method was replaced by the 3/9 method in ANSI/IEEE C37.09.

Figure A.2 shows that the 15/2, 15/2M, 15/2MPLUS and 15/2MF methods are close to one another with the 15/2M and 15/2MF methods offering the best choice in terms of LTPD for the specified β risk. The 15/2M or 15/2MF methods seem to be the best balance of simplicity and risk. The α and β risks are compared in Figures A.4 and A.5, respectively.

For the 15/2M and 15/2MF sampling plans two indices have now been identified: AQLs of 4,4 % and 5 % at an α risk of 5 % and LTPDs of 29,1 % and 29,2 % at a β risk of 10 %, respectively (Figures A.4 and A.5). A further index used in conjunction with sampling plans is the Average Outgoing Quality Limit (AOQL). This concept derives from the relationship between the incoming quality before inspection and the outgoing quality after inspection and rejected lots are screened. When the incoming quality is perfect, outgoing quality will also be perfect. However, when incoming quality is very bad, the outgoing quality will still be perfect because the sampling will cause all lots to be rejected and detail inspected. That is, at either extreme of very good or very bad incoming quality, the outgoing quality is very good. Between these two extremes is the point at which the percent of defectives in the going material will reach its maximum and this point is the AOQL.

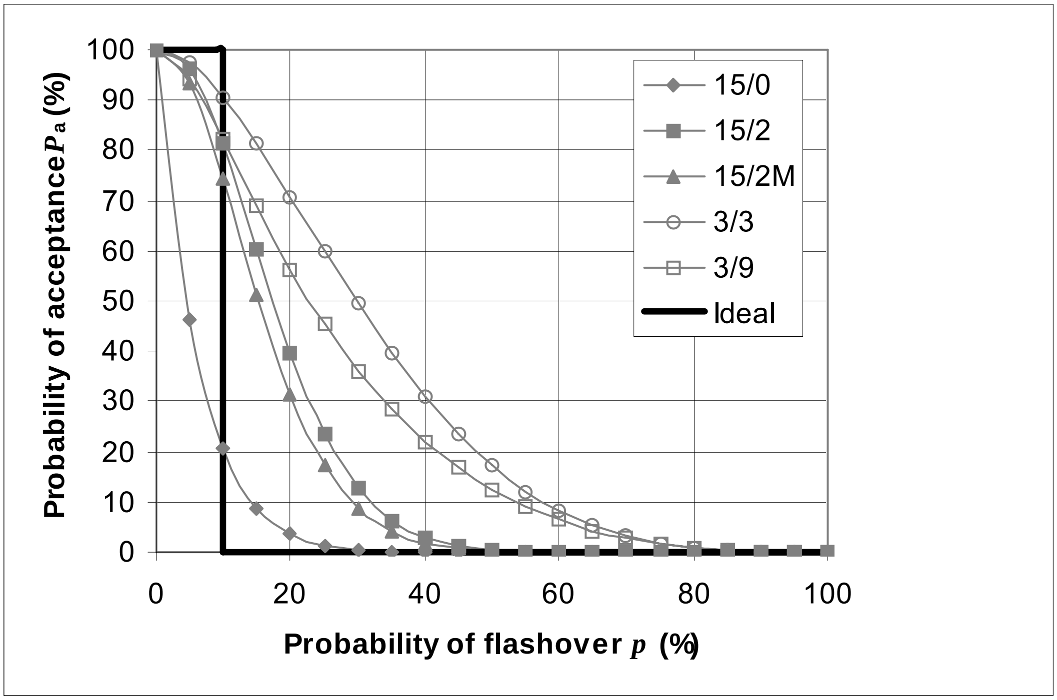


Figure A.3 - Ideal sampling plan for AQL of 10 %

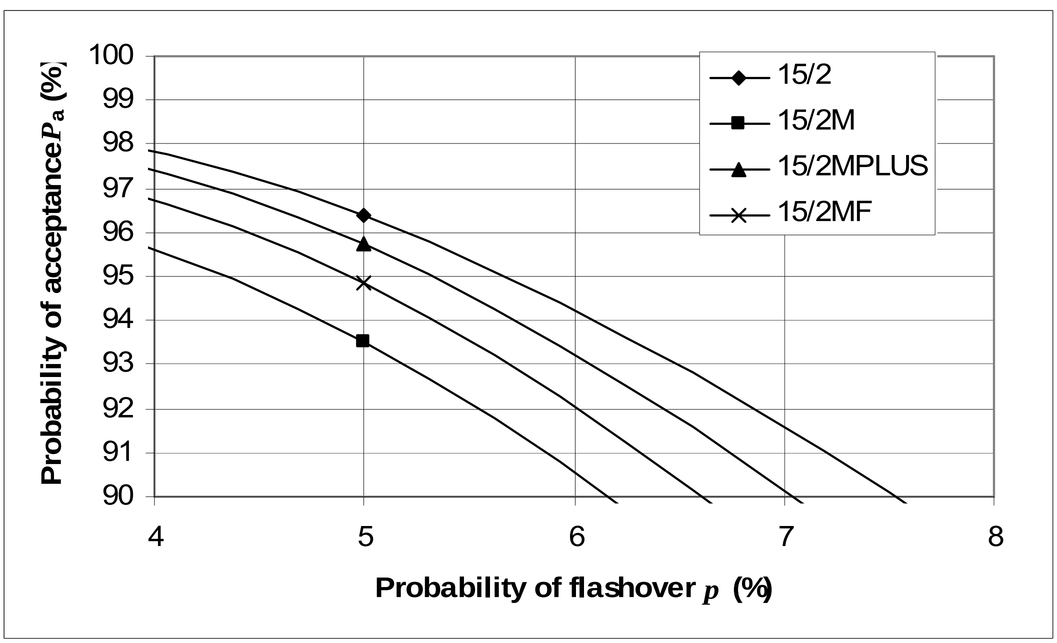


Figure A.4 - α risks for 15 impulse based methods

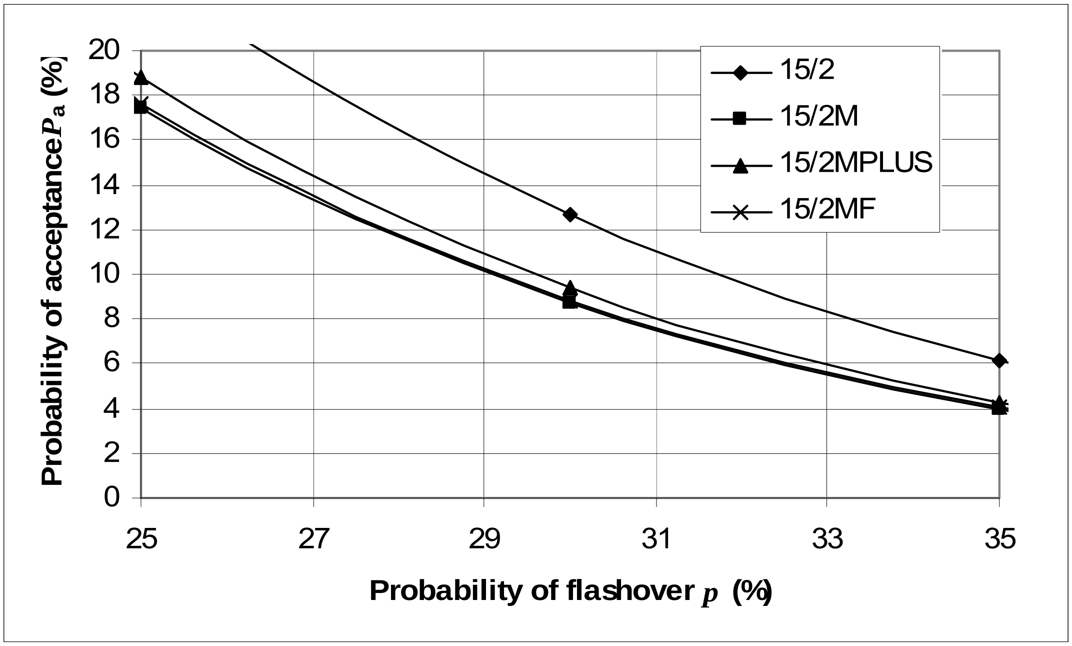


Figure A.5 - β risks for 15 impulse based method

For a relatively large number of objects which are supposed to be identical and consequently are tested under the same condition the Average Outgoing Quality (AOQ) is expressed as:

$$\text{AOQ} = pP_{\text{a}} + (o)P_{\text{r}} = pP_{\text{a}}$$

where p is the incoming quality (probability of flashover), P_{a} is the probability of acceptance as before and P_{r} is the probability of rejection. The calculation is based on the premise that all defective units in the samples in accepted lots are retained and those in rejected lots are repaired or replaced which explains the (o) term in the AOQ expression. The two extremes noted above for the 15/2M method (Figure A.2) are:

P_{a} = 1 (100 % acceptance), p = 0

and

P_{a} = 0 (0 % acceptance), $p \geq 0{,}5$

giving an AOQ of zero (best possible outcome).

The AOQ curves for the 15 impulse based methods are shown in Figure A.6. The crest value of the curves is the AOQL and the 15/2M method has the lowest AOQL at about 7,8 % with the 15/2MF method next at 8 %. This result is obvious from the OC curves in Figure A.2 and the expression for AOQ. The result would be less obvious if the OC curves crossed over one another. Using the lowest value of the term AOQL may appear contradictory but one should remember that the AOQ is measured in terms of defects: the lower the number of defects the higher the quality. The 15/2M method thus gives the highest product quality but has the disadvantage that it would reject the test object if the second of two flashovers occurred during the verification impulses. The 15/2MF method does not have this disadvantage.

The 15/0 method has been proposed in the past and is included here for completeness (Figure A.1). This method is not a consideration for a number of reasons. It does not recognize the notion of self-restoring insulation nor that the probability of flashover is never zero, and statistically it approaches 100 % inspection which is unrealistic given that the test is a type test. The AQL for an α risk of 5 % is extremely low so from a manufacturer's perspective product quality must be extremely (and probably unnecessarily) good to avoid a very high rejection rate. The result is (probably unnecessarily) higher costs.

A comparison of the operating characteristic curves for the 15/2 and 3/9 methods are shown in Figure A.7.

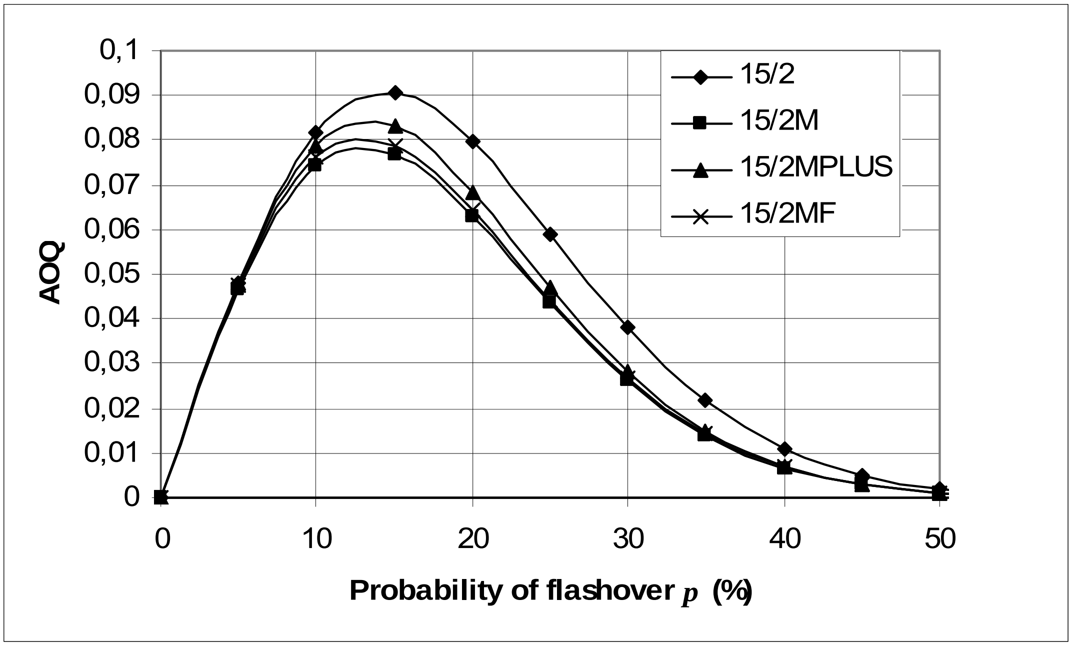


Figure A.6 - AOQ for 15 impulse based methods

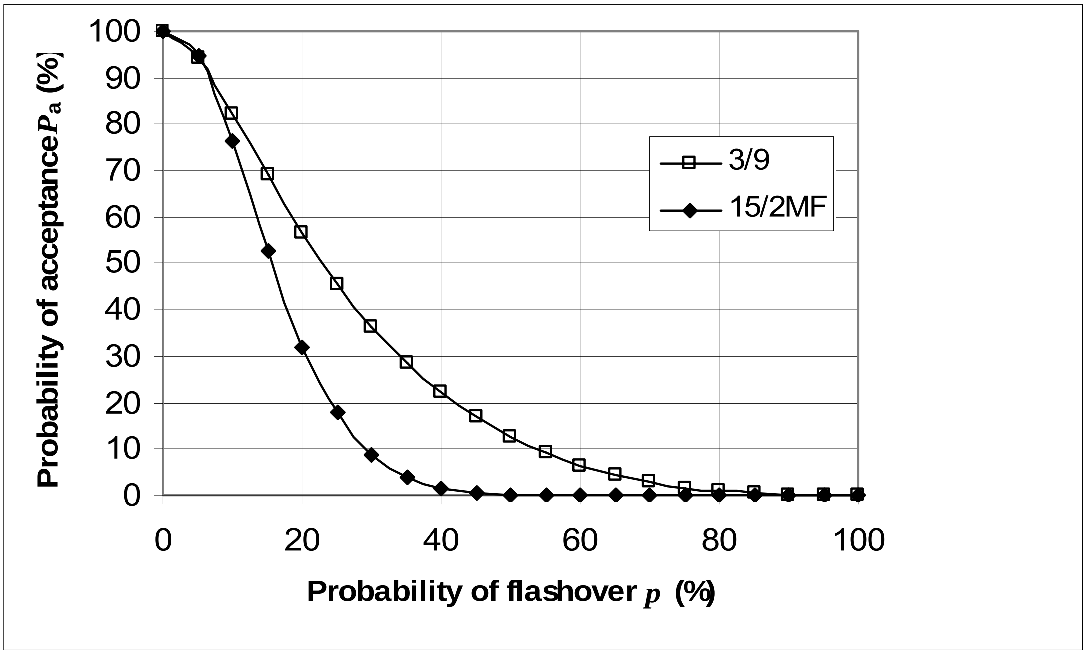


Figure A.7 - Operating characteristic curves for 15/2MF and 3/9 test method

Readers interested in a more detailed description of statistical sampling are referred to the referenced textbooks on quality control [2, 3, 4].

A.3 References

[1] I. Miller and J.E. Freund, "Probability and Statistics for Engineers," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1965.

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Appendix B

P_a equations for various test methods

Test method	P_a
15/0	$(1-p)^{15}$
15/2	$(1-p)^{15}+15p(1-p)^{14}+105p^2(1-p)^{13}$
15/2M	$(1-p)^{15}+10p(1-p)^{14}+45p^2(1-p)^{13}+\left[p(1-p)^{10}+10p^2(1-p)^9\right]\times$ $\left[(1-p)^5+(1-p)^6+(1-p)^7+(1-p)^8+(1-p)^9\right]+p^2(1-p)^{10}\left[(1-p)^5\right.$ $\left.+2(1-p)^6+3(1-p)^7+4(1-p)^8\right]$
15/2MF	$(P_a \text{ for 15/2M})+p^2(1-p)^{10}\left[5(1-p)^9+4(1-p)^{10}+3(1-p)^{11}+2(1-p)^{12}+(1-p)^{13}\right]$
15/2MPLUS	$(P_a \text{ for 15/2M})+\left[p^2(1-p)^{10}+10p^3(1-p)^9\right]\times\left[5(1-p)^9+4(1-p)^{10}\right.$ $\left.+3(1-p)^{11}+2(1-p)^{12}+(1-p)^{13}\right]+p^3(1-p)^{10}\left[10(1-p)^8+10(1-p)^9\right.$ $\left.+9(1-p)^{10}+7(1-p)^{11}+4(1-p)^{12}\right]$
3/3	$(1-p)^3+3p(1-p)^5$
3/9	$(1-p)^3+3p(1-p)^{11}$

Appendix C

Summary of 15/2 based test methods and 3/9 method

Method	Description	Number of Acceptable Outcomes	AQL (%)	LTPD (%)	AOQL (%)	Comments
15/2	Basic 15 impulses, two (2) disruptive discharges permissible. No disruptive discharge on self-restoring insulation.	3	5,7	31,8	9,1	Establishes fundamental principles of basic 15 impulses and maximum two (2) disruptive discharges permissible; depending on when the discharges occur may not be possible to distinguish between disruptive discharges across self- and non-self-restoring insulation.
15/2M	Modified 15/ method, last disruptive discharge must be followed by five (5) withstands adding one (1) to five (5) verification impulses as necessary.	23	4,4	29,1	7,8	Intended to deal with the disadvantage of the 15/2 plan as noted above, it would fail the test object if a disruptive discharge occurs during the verification impulses even if only one (1) such discharge had occurred during the basic 15 impulse
15/2MPLUS	As for 15/2M except that one (1) disruptive discharge (second or third such discharge) in the verification impulses	93	5,3	29,6	8,4	Apparently intended to deal in turn with the disadvantage of the 15/2M plan, it is overly complex (high number of acceptable outcomes) and in any case violates the principle of maximum two (2) disruptive discharges permissible
15/2MF	As for 15/2M except that one (1) disruptive discharge permissible in the verification impulses if only one such discharge occurred in the basic 15 impulses	38	5	29,2	8	Addresses the disadvantages of the 15/2 and 15/2M while retaining the principle of maximum two (2) disruptive discharges permissible; however the argument is made that up to five (5) verification impulses is an unnecessarily high number
3/9	Basic 3 impulses, one (1) disruptive discharge permissible in which event nine (9) further impulses applied with no disruptive discharges permissible	3	4,6	53,5	11,2	Used only in the United States

6 Transport, storage, installation, operation and maintenance

The IEC 62271-1 and IEC 602271-100 subclauses relevant to this chapter are:

10 Rules for transport, storage, installation, operation and maintenance

10.2.101 Guide for commissioning tests

6.1 Introduction

The purpose of this section of the guide is to provide additional information to assist in ensuring that the circuit-breaker is transported, stored, installed, operated and maintained in a manner that maximises reliability and availability for the life of the equipment.

The circuit-breaker should have been routine tested before transportation to prove that it is of suitable quality and considered by the manufacturer to be suitable for use on a high-voltage network. It must then be transported, stored, installed, operated and maintained in accordance with the instructions given by the manufacturer. These instructions should be provided before the delivery of the equipment. Ideally they should be available at the time of purchase or technical assessment for purchase.

The recommended approach to the management of the circuit-breaker asset evolves during the life of the equipment from the basis of the initial recommendations of the manufacturer. This initial program can be optimised using the experience of the user and the manufacturer. The development of management strategies for circuit-breakers is outside the scope of IEC 62271-100. CIGRE provides important reference documents covering reliability [1], condition monitoring [2] and life management [3] of circuit-breakers.

6.2 Transport and Storage

A circuit-breaker that has met all factory testing and inspection requirements is considered to be correctly manufactured and suitable for use on a high-voltage network. It is therefore important to ensure the circuit-breaker is transported and stored in a manner that does not cause damage to the equipment.

IEC 62271-1 emphasises the need for protection from damage caused by moisture and vibration during transport and storage. Appropriate instructions must be provided by the manufacturer and should include packing units, packaging description, dimensions, weights and storage requirements.

Consideration may also be necessary for any special conditions that may be imposed by the circumstances of the project when determining transport and storage options. This includes any environmental changes that are likely to be experienced during transportation and storage, for example ambient temperature, pressure, humidity and pollution especially from salt (sea/coastal) environments. A particular consideration may be whether the packed equipment should be capable of being stored outdoors for a defined period without being damaged. Equipment should also be packed or crated in a manner suitable for stacking and for handling by forklift or other appropriate means and arranged so that complete items of plant may be delivered to separate sites independently.

Each packing case should contain a list detailing the contents of the case. There should be clear indication of any special handling conditions, which should preferably be repeated on the container. Shock indicators are a useful method of determining whether the equipment has been subjected to high impacts during transportation.

If any equipment is shipped with sealed gas, then it is recommended that any gas connection should be marked with the pressure, temperature and date of sealing. Any valves or other fittings liable to damage during shipment should have covers or shall be replaced by plugs.

A power supply may also be required for connection to the anti condensation heaters during storage. Clear instructions must be provided to ensure safe connection of such supplies and potential damage to sub-components adjacent to the heaters.

The requirements for the packing and storage of spare parts need to be considered to ensure they can be appropriately stored, identified and handled.

Any damage or doubts regarding the condition of the circuit-breaker should be referred to the manufacturer.

6.3 Installation

Sections 10.2.1 to 10.2.4 of IEC 62271-1 describe the unpacking, lifting, assembly, mounting and connections to the circuit-breaker. Connections include the high-voltage and current connections, auxiliary circuits, liquid or gas systems and earthing.

It is important that the required information is provided for the safe and effective unpacking, lifting and assembly of the circuit-breaker on the appropriate foundations.

Responsibilities for erection and commissioning of the circuit-breakers need to be defined before these activities are commenced. It is important to ensure that the erection and commissioning staff are competent and there is adequate expert supervision. Involvement of the manufacturer should be considered and there may be a need for qualification of staff in the erection and commissioning of each type of circuit-breaker. Responsibility should also be defined for the supply of SF_6, other gases, and hydraulic oil where appropriate, for filling to operational pressure.

Confirmation should be made that correct gas transport pressures have been maintained and subsequent filling is to the correct pressure. The use of recycled gas complying with IEC 60480 is encouraged provided there is agreement with the manufacturer. The manufacturer is to state any requirements for the use of recycled gas. All necessary testing to prove the quality of the gas is recommended.

Within the bounds of practicality there is to be no discharge of SF_6 due to the impact of SF_6 on the environment and potential health and safety implications. SF_6 should not be released imprudently to the atmosphere. Any unwanted or waste SF_6 should be recovered for recycling.

Confirmation should be made of all connections including high-voltage, secondary and earthing connections. The main high-voltage connections should be installed as designed to ensure terminal loading forces and support bending moments are not exceeded for all environmental, operational, fault and seismic conditions. This requirement is important for adjacent equipment as well as the circuit-breaker.

Checks should include correct assembly, avoidance of damage, correct gas pressures and correct earthing.

6.4 Commissioning

Commissioning tests are recommended to be performed following installation. The purpose of these tests is to confirm the following:

- transport and storage have not damaged the circuit-breaker;
- separate units are compatible;
- assembly has been performed correctly;
- the circuit-breaker will operate correctly.

Commissioning tests are particularly important when a large part of the assembly and/or adjustment is performed on site.

Repetition of the full program of routine tests already performed in the factory should be avoided.

If major sub-assemblies are combined at site, without previous tests on the complete circuit-breaker, then a minimum of 50 no-load operations are to be performed on site. Deferred routine tests may be included in the 50 operations because both site routine tests and commissioning tests confirm the correct operation of the circuit-breaker.

The manufacturer shall provide instructions for inspection and tests that should be made after installation and all connections have been made. The results shall be provided in a commissioning test report. The commissioning test program shall be based on the manufacturer's recommendations and should be agreed before the program is commenced.

Subclause 10.2.101 of IEC 62271-100 contains guide for commissioning tests. A commissioning test program is required that may include but not be limited to the tests included in the guide. The nominated tests are comprehensive but it may be appropriate to exclude some tests or include additional tests as appropriate. The selection of tests should consider the type and construction of the circuit-breaker as well as the conditions of transportation, storage and installation. The guide includes tests and checks in the following categories.

- general checks including assembly, tightness, external insulation, paint, corrosion protection, operating devices, earth connection and operations counter;
- checks of electrical circuits including wiring, position indication, alarms, lockouts, heating and lighting;
- checks of the insulation including filling pressure and quality (in accordance with IEC 60376, IEC 60480 and IEC 61634 for SF_6 [4,5,6];
- checks on operating fluids including levels, filling pressure and purity;
- site operations;
- Insulating and interrupting fluid alarm and lockout pressures on rising and falling pressures;
- characteristic rising and falling operating pressures for hydraulic and pneumatic systems including lockout, low pressure alarm, safety valve and pumping device cut-in and cut-out;
- power consumption during operations;
- verification of the operating sequence;
- closing and opening times of each pole including control and auxiliary contacts;
- recharging time of the operating mechanism;
- mechanical travel characteristics where the circuit-breaker has been assembled as a complete circuit-breaker for the first time or where all or part of the routine tests have been performed on site;

  These mechanical travel characteristics may be used as a reference for future maintenance. Due to differences in the measurement equipment, the results may differ from the information provided by the manufacturer;

- opening, closing and auto reclosing at the minimal functional pressure for operation;
- the time during which the circuit-breaker remains closed during a CO operation including an anti-pumping check;
- behaviour of the circuit-breaker on a closing command while an opening command is already present;
- the application of an opening command on both releases simultaneously;
- protection against pole discrepancy;
- dielectric tests on auxiliary circuits taking care not to damage vulnerable sub components;
- measurement of the resistance of the main circuit;

Procedures need to be included in the instructions for any adjustments that may be needed for correct operation.

Recommendations shall also be provided for any relevant measurements that should be made and recorded to assist with future maintenance decisions.

The instructions need to be sufficient for final inspection and putting into service.

6.5 Operation

The manufacturer needs to provide suitable instructions and the user needs to have suitable understanding of the equipment characteristics and principles of operation. This must include the relevant safety requirements and the actions that must be taken for operation, isolation, earthing, maintenance and testing. These instructions should preferably be agreed and understood by the user prior to installation and ideally at the time of purchase.

6.6 Maintenance

The manufacturer should provide a maintenance manual that includes the extent and frequency of the recommended maintenance and a description of the maintenance work. Suitable drawings should clearly identify assembles, sub assemblies and significant spare parts necessary for the maintenance and repair of the equipment. Measurement values and tolerances should be included which may require corrective action. Specifications should also be included for any materials and tools needed during maintenance. The manufacturer should also be prepared to state their policy for the continued supply and availability of spares. The maintenance manual and any training must adequately cover the various hazards that may create: a risk to personal safety; a risk to the environment; or damage to the circuit-breaker. These hazards may include electrical, mechanical, thermal, operational and chemical aspects.

The user needs to ensure maintenance staff are suitably competent for the task. The user should also ensure suitable records are kept of the history of service, maintenance, failures and measurements taken.

It is important that suitable information is exchanged between the manufacturer and user during the life of the equipment. This should include failure information, special instructions and refinements to the recommended maintenance procedures. It is important that both parties provide information.

Further tools and techniques are available to optimise the performance of the equipment and effectiveness of the maintenance effort. On-line condition monitoring and Reliability Centred Maintenance (RCM) are examples of emerging strategies that can be applied to circuit-breakers. Information gained by the use of such techniques should be shared with the manufacturer. CIGRE provides comprehensive analysis of the strategies available in these areas [2,3].

6.7 References

[1] CIGRE Technical Brochure 83, Final Report of the Second International Enquiry on High-voltage Circuit-breaker Failures and Defects in Service, June 1994.

[2] CIGRE Technical Brochure 167, User Guide for the Application of Monitoring and Diagnostic Techniques for Switching Equipment for Rated Voltages of 72.5kV and Above, August 2000.

[3] CIGRE Technical Brochure 165, Life Management of Circuit-breakers, August 2000.

[4] IEC 60376:1971, Specification and Acceptance of New Sulphur Hexaflouride

[5] IEC 60480:1974, Guide to the Checking of Sulphur Hexaflouride (SF_6) Taken from Electrical Equipment

[6] IEC 61634:1995, High-Voltage Switchgear and Controlgear – Use and Handling of Sulphur Hexaflouride (SF_6) in High-voltage Switchgear and Controlgear.

7 Gas and vacuum tightness

The IEC 62271-1 and IEC 602271-100 subclauses relevant to this chapter are:

5.15 Gas and vacuum tightness

6.8 Tightness tests

7.4 Tightness test

7.1 Specification

From a maintenance or environmental approach, it would be advisable to specify a "leakage-free" or "fully-tight " equipment. Unfortunately it is not realistic for at least two reasons:

- Perfect tightness does not exist: every wall allows gas to get through (the flow of SF_6 gas through a cast aluminium wall has been measured);
- Tightness is measured by the leakage rate, and the smaller the specified leakage rate, the more difficult to measure it, in particular to cover decades of years.

As a result, specification should be based on the actual need, which depends on the system class and on the use. Since the standard was addressed to any type of high-voltage circuit-breaker, it was necessary to classify the different pressure systems. At the time of the first issue of tightness specification for high-voltage circuit-breakers, the main concern was to link the tightness to the maintenance schedule.

"Controlled pressure systems" are automatically replenished. At the time of the first draft, this class applied mainly to air-blast circuit-breakers; nowadays the main application is pneumatic operating mechanisms, or pressure systems with internal recharge after operation. For external tightness of compressed air systems, there is no ecological question and the specification for tightness is only linked to the compressor plant performance.

"Closed pressure systems" are those which are replenished only periodically, for instance during maintenance. Tightness can be specified from an ecological approach. By specifying the annual gas leakage rate in %/year, easy calculation of the amount of gas escaped per year is possible. Subclause 5.15.2 of IEC 62271-1 specifies tightness for SF_6 with values of 1 and 0,5 %/year. The original value of 3 %/year specified in Annex EE of the 4th edition of IEC 60056 published in 1987 is no longer specified, because service records show that 1 %/year can usually be met.

"Sealed pressure systems" are designed not to need replenishment during their whole expected service life. Their tightness should be demonstrated accordingly, to show that the minimum functional density will not be attained before the expected end of life.

7.2 Testing

The figures used to specify gas tightness of closed pressure systems cannot be measured directly. To check these characteristics, the current method is to measure the leakage rates of each component and to sum them up as indicated in Annex E of IEC 62271-1. As a result, the manufacturer is led to specify the tightness of each component or sub-assembly to be tested, so that the complete system meets the global specification. But a safety margin must be taken between the individual figures issued from that calculation and those to be accepted in actual testing in order to cover various factors such as:

a) the inaccuracy of the measurement itself;

b) the extrapolation of the results when the test is performed with a tracing gas or at a pressure different from those in service;

c) the variation of the leakage rate in the time due for instance to temperature change;

d) Ageing of materials, of gaskets in particular.

Some of these remarks are also applicable to sealed pressure systems.

Testing of the tightness between separate compartments is necessary when their rated filling densities are different.

8 Grading capacitors

8.1 Introduction

Grading capacitors are accessories to high-voltage circuit-breakers and are mainly used to control the voltage distribution across the individual breaking units of a multi-unit circuit-breaker. They are mounted in parallel with the breaking units.

The presence of additional capacitance across the circuit-breaker contacts modifies the line side TRV in the case of short-line faults. For this reason, capacitors can also be found on single-unit circuit-breakers. In the latter case, they are mounted in parallel with the breaking unit or to earth. Their function is solely to influence the line side TRV, they do not participate in voltage distribution. This type of application is not dealt with in this section

Grading capacitors consist of a number of capacitor packages inside an insulated housing. Design and test requirements are given in IEC 62146-1 [4].

8.2 Capacitor characteristics

8.2.1 Equivalent circuit

A possible a.c. equivalent circuit of a capacitor can be approached by the circuit given in Figure 5.

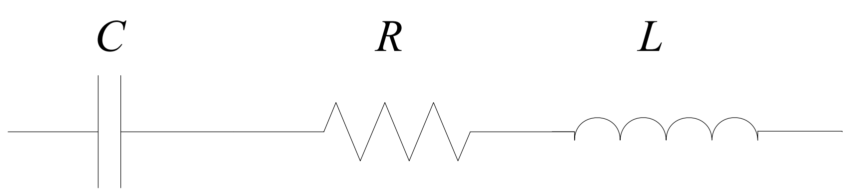

Figure 5 – Equivalent circuit of a grading capacitor

C represents the capacitance of the grading capacitor and R the losses and L the internal inductance.

8.2.2 Tanδ, power factor and quality factor

For the determination of tanδ, power factor and quality factor, the inductance in Figure 5 can be neglected. The equivalent circuit is given in Figure 6.

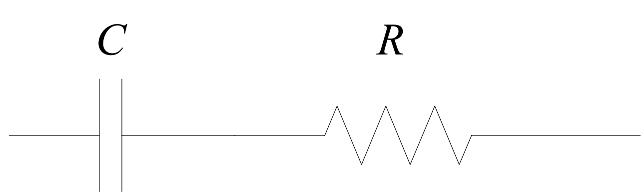

Figure 6 – Equivalent circuit for determination of tanδ, power factor and quality factor

Figure 7 shows the vector diagram of the capacitor impedances.

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[4] To be published.

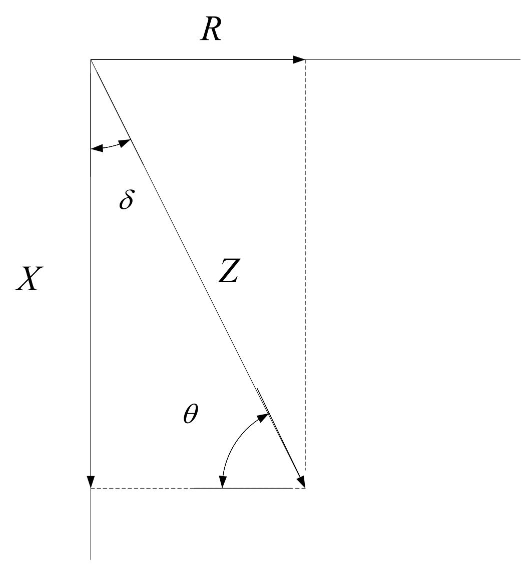


Figure 7 – Vector diagram of capacitor impedances

The following capacitor characteristics can be derived:

$$X = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + \frac{1}{\omega^2 C^2}}$$

The dielectric loss angle is δ (see Figure 7). The dissipation factor $\tan\delta = \frac{R}{X} = \omega RC$ is also known as Dissipation Factor (DF).

Power factor (PF) = $\cos\theta$ = $\sin\delta$ = R/Z.

For relatively low values of R, Z is approximately equal to X, in other words: δ, $\sin\delta$ and $\tan\delta$ are equivalent. As a result, the Power Factor and Dissipation Factor are nearly equal.

The quality factor Q = X/R = $1/\tan\delta$.

8.2.3 Grading capacitor resonance frequency

The grading capacitor has its own internal resonance frequency at the point where the impedances cancel each other. To determine the internal resonance frequency, the circuit shown in Figure 5 is used and the resistance is neglected.

The internal resonance f_i frequency is: $f_i = \frac{1}{2\pi\sqrt{LC}}$

8.3 Application considerations

8.3.1 Shocks and vibration

Grading capacitors mounted on circuit-breakers are exposed to shocks and vibrations as a result of the operation of the circuit-breaker. The manufacturer should ensure that the grading capacitors have been properly type tested.

8.3.2 Ferroresonance

When a circuit-breaker with grading or parallel capacitors is installed in a substation, the capacitors may form a resonance circuit together with any ferromagnetic inductance (i.e. magnetic instrument transformers and power transformers) present in the substation. This can give rise to ferroresonance in case the circuit-breaker is in the open position.

The risk of ferroresonance increases with increasing grading capacitance values.

8.3.3 Shunt reactors

Shunt reactor switching may expose the grading capacitors to the effect of a reignition of the interrupter. The steep transient of the second parallel oscillation stresses the capacitors and may puncture the dielectric of the individual capacitor packages inside the grading capacitor.

8.3.4 Exposure to d.c. voltages

In applications where capacitive currents are switched (capacitor banks, no-load overhead lines and no-load cables), the load side of the circuit-breaker remains at a d.c. voltage whereas the source side is exposed to a power frequency voltage. In such applications the grading capacitor may be exposed to a d.c. voltage.

The grading capacitor has to withstand the discharge of the trapped charge in the grading capacitor during closing of the circuit-breaker or restrike during opening.

9 Consideration of X/R ratio in the application of high-voltage circuit-breakers

9.1 Introduction

The considerations given in this section are based on the assigned ratings of the circuit-breaker. Since the asymmetrical current on at least one phase associated with interrupting a three-phase fault may be the maximum peak current that a circuit-breaker has to interrupt, this has to be carefully evaluated. The current is said to be asymmetrical since it consists of two components: an a.c. component and a d.c. component. The d.c. component arises because there is no instantaneous change in the flux levels possible in magnetic circuits associated with a sudden short-circuit on the system. The short-circuit requires an instantaneous change in the current level from what had been the load current to the much greater short-circuit current. The magnetic circuits are associated with the iron flux circuits found on the system in the generators and transformers. For asymmetrical current the basis of rating is a d.c. time constant of 45 ms [1].

The purpose of this section is to explore the implications of applications with d.c. time constants other than 45 ms. However, in doing this the scope must be limited since the amplitude, duration and the di/dt at current zero all change as the d.c. time constant changes. In general higher asymmetry results in a lower du/dt and peak value of the TRV, reducing the stress during the dielectric recovery. This fact has been disregarded in this section and therefore the results can be considered conservative. The end result should be a reasonable approximation of the assigned rating. IEC 62271-100 introduces tolerances for testing purposes during the arcing interval on peak current amplitude and duration of ±10 % of rating on the last loop of current prior to interruption. There is an additional restriction if the tolerances on current amplitude cannot be fulfilled that the product "Ixt", "I" being the required peak value of the last short-circuit current loop and "t" being the required duration of the last short-circuit current loop, is between 81 % and 121 % of the required values.

The application of generator circuit-breakers is beyond the scope of these considerations. With applications close to generators the possibility of delayed current zeros may occur. This generally occurs when the generator is lightly loaded and is operating with a leading power factor. When the generator is carrying load with a lagging power factor the asymmetry is generally lower and delayed current zeros are not expected. Additional information on this subject is given in [2].

9.2 Network reduction

The rate of decay of the d.c. decrement is usually expressed as a time constant. As it turns out the effective X/R ratio at the point of fault defines this time constant. While in reality there will be a decrement in both the a.c. and d.c. components of the short circuit current, for purposes of this examination the decrement of the a.c. current is ignored.

It should be noted that the effective X/R ratio is not the simple ratio of the R-jX typically obtained by network reduction short-circuit programs. Experience has shown that using the R and X values obtained by the typical network reduction short-circuit program will give the correct short-circuit current. However, the d.c. time constant based on the ratio of these values will generally be less than the correct value.

The IEEE application guide C37.010 [3] suggests that the network reduction be done by making the R and X reductions separately. This greatly simplifies the work when calculations are done manually. It also results in a conservative time constant. An **E**lectro **M**agnetic **T**ransient **P**rogram (EMTP) used for this type reduction should provide a correct answer. However, this is a very sophisticated program generally requiring personnel skilled in its daily use to obtain satisfactory results.

9.3 Special case time constants

With the publication of the first edition of IEC 62271-100 the explicit concept of a circuit-breaker being able to deal with X/R ratios or time constants other then the standard time constant of 45 ms was introduced for the first time. IEC 62271-100 specifies additional “special cases time constants” of 60, 75 and 120 ms in subclause 4.101.2. In 4.101.2 b) the following insight is provided:

- 120 ms for rated voltages up to and including 52 kV;
- 60 ms for rated voltages from 72,5 kV up to and including 420 kV;
- 75 ms for rated voltages 550 kV and above.

For application of circuit-breakers on power systems IEC 62271-100 calls attention to the fact that not all applications fall within the confines of existing standards. This is a logical extension for the following reasons:

- The lower voltage circuit-breakers will frequently be applied close to generation or step down transformers which exposes the circuit-breakers in such locations to the much longer time constants. Medium voltage circuit-breakers will most often be applied in substations with occasionally one being close to a step-down or step-up transformer at the time of fault initiation. This reflects less expected exposure and lower probability of short-circuit current levels near the circuit-breaker rating.
- At the higher voltages bundled conductors may be used and the circuit-breaker again may be close to transformers. The bundled or larger diameter conductors will contribute to the higher X/R ratio. At the same time in terms of circuit-breaker rating these same circuit-breakers may be remote enough on the system that the actual short-circuit current seen by the circuit-breaker is significantly reduced below the actual circuit-breaker ratings.

For the circuit-breaker application engineer this raises the question of how to evaluate the individual applications. This section tries to provide some guidance.

9.4 Guidance for selecting a circuit-breaker

To evaluate the effect of different d.c. time constants some general observations can be made. For cases in which the actual short circuit current is less but the d.c. time constant is greater the $\mathrm{d}i/\mathrm{d}t$ of the current and the amplitude of the minor loop will be less than the rated value. The arc energy represented by the area of the major loop of current is probably one of the most important considerations. The amplitude and duration of the major loop of current are directly related to the d.c. time constant. Also of importance is the total arc energy represented by the total area measured from the point of circuit-breaker contact separation to final arc extinction.

In an effort to evaluate the effect of different d.c. time constants the time constants of 45 ms, the standard, and extended time constants of 60, 75, 90 and 120 ms were examined. The addition of 90 ms was made to provide a uniform spread in the data to be developed for comparison.

The methodology to evaluate the effect of different time constants is as follows:

a) Solve Equation 15 for the total current assuming no a.c. decrement over a range of time (t) sufficient for the period of interest.

$$i_{\text{total}} = \left(\mathrm{e}^{-\frac{2\pi f t}{\tau}} - \cos(2\pi f t) \right) \sqrt{2} \times i \qquad (15)$$

where i_{total} is the total current

f is the power frequency

τ is the d.c. time constant of the system

b) Using Equation 15, determine the current i_{total} for each of the selected time constants. Listed below are the approximate X/R ratios for these time constants for both 60 Hz and 50 Hz.

Table 6 – Relationship between time constant and *X/R* value

Time constant ms	*X/R* 60 Hz	*X/R* 50 Hz
45	17,0	14,1
60	22,6	18,8
75	28,3	23,6
90	34,0	28,3
120	45,2	37,7

As a refresher one time constant is defined as e^{-1}. For example to obtain a time constant of 45 ms in Equation (15), the product of $\frac{\omega}{\tau} \times 0{,}045 = 1$, with $\omega = 2\pi f$. If the value 17 is used for X/R in a 60 Hz calculation it gives a time constant of 45 ms. From this it is obvious that the X/R ratios must change in proportion to the change in frequency for the time constants to be the same for both 50 and 60 Hz systems. A better form of Equation 15 is given in Equation 16:

$$i_{\text{total}} = \left(e^{-\frac{t}{\tau}} - \cos(\omega t) \right) \sqrt{2} \times i \qquad (16)$$

where τ is the time constant of interest.

c) Having solved Equation 16 for the continuous values, the next step is to decide where the interruption will take place. The time sequence events in the operation of a circuit-breaker that always precede the actual interruption and tend to establish the most likely time for interruption are:

relay time;

circuit-breaker minimum contact part time (minimum opening time plus relay time);

minimum arcing time.

The next available current zero after the sum of the above times has elapsed is the earliest that interruption can take place. It may not occur at this time for all situations and types of circuit-breakers. It is a reasonable assumption for modern SF_6 or vacuum circuit breakers.

Some assumptions:

a) The arc voltage is constant during the period of arcing. This allows the arc energy to be represented by the $I \times t$ area under the current curve;

Since the smaller total current with the longer d.c. time constant (compared with the rated short-circuit-current and the standard time constant) has a larger d.c. component, the di/dt will always be less and the circuit-breaker should still interrupt at the normal current zero if it has met all other criteria;

b) If the energy represented by the $I \times t$ area under the current curve is less than that of the standard wave, the interruption will be successful;

c) If the energy represented by the $I \times t$ area under the current curve is equal to or greater than that of the standard interruption, the interruption will be unsuccessful. This may need to be applied to the major loop specifically as well as the total period.

The $I{\times}t$ areas X under the current curve can be obtained by solving Equation 17.

$$X = \int_{t_1}^{t_2} f(t)\mathrm{d}t \qquad (17)$$

where: $f(t)$ is the total current i_{total} as given in Equation 16

t_1 is the contact part time, the minimum opening time plus the relay time

t_2 is the time at the current zero where interruption could occur

This integration may need to be done in parts.

The general guidance is to de-rate a circuit-breaker 1 class or approximately 80 % to deal with greater X/R ratios or d.c. time constants. The question that must be answered is whether this is sufficient. IEC 62271-100 does not propose to test at current ratings or time constants other than rated. For test purposes IEC 62271-100 gives the following asymmetry criteria to be fulfilled when performing T100a:

- last current loop amplitude;
- last current loop duration;
- asymmetry level at current zero.

Using the above methodology the following cases were examined.

9.4.1 Case 1

Assumptions: Circuit-breaker rating 63kA, 60 Hz.

- Relay time 8 ms (0,5 cycles or 8,333 ms. is the correct value but 8 ms was chosen to have round numbers. The slight difference is easily corrected with a slightly different assumption for the other numbers);
- Minimum opening time 21 ms;
- Minimum arcing time (interruption after minor loop) 8 ms;
- Frequency 60 Hz;
- Time constant 45 ms;
- The -sign of the current area for the minor loop is ignored in the summation of the areas.

Table 7 – Comparison of current loop areas after contact separation, case 1

Row	Current rating kA	Time constant ms	Area of 1st major loop kAs	Area of 1st minor loop kAs	Area of 2nd major loop kAs	Total area kAs
1	63	45	0,040	0,174	0,806	1,020
2	50	60	0,043	0,101	0,718	0,862
3	50	75	0,052	0,078	0,778	0,908
4	50	90	0,059	0,062	0,824	0,945
5	50	120	0,070	0,043	0,890	1,003
6	50	80	0,055	0,072	0,794	0,921
7	40	120	0,056	0,034	0,712	0,802

Particular points of Table 7:

a) Row one provides the reference values for a 63 kA rating with τ = 45 ms;

b) The second row shows the requirements for a 50 kA rating with τ = 60 ms. The summed areas are less than the reference rating for all loops of current thus assuring a satisfactory application;

c) The area of the last major loop and the total area in the third row are less than that of the reference rating;

d) The rating has been kept at 50 kA but the time constant has been increased to 90 ms in the fourth row. Note that the area of the major loop is now greater than the reference value of 1. This would be judged to be unsatisfactory;

e) In row 5 the rating is still 50 kA but the time constant has been further increased to 120 ms. The area of the major loop has increased even more. Note that the total area is still less than the reference value of 1 but because of the major loop area it is unsatisfactory for application;

f) In row 6 the rating is still 50 kA and a time constant has been selected that results in a major loop area that is close but less than the reference area of row 1;

g) It is demonstrated that the area of the major loop for 40 kA rating with τ = 120 ms is covered by that in the reference case of 63 kA rating with τ = 45 ms. However, the performance is not necessarily demonstrated by testing for the reference case as the duration of the major loop, hence the arcing time, is much less than in the 40 kA τ = 120 ms (respectively 10,52 ms and 12,52 ms as shown in Table 9).

From the above it can be seen that in using the area criteria, the area of the major loop is important. While the total area overall is greater for the 63 kA circuit-breaker with the 45 ms time constant, the area for the major loop for a 50 kA circuit-breaker exceeds that of a 63 kA circuit-breaker if the d.c. time constant exceeds 80 ms.

9.4.2 Case 2

Assumptions: Circuit-breaker rating 63 kA, 50 Hz.

- Relay time 10 ms;
- Contact part time 26 ms;
- Minimum arcing time (interruption after minor loop) 8 ms;
- Frequency 50 Hz;
- Time constant 45 ms.

Table 8 – Comparison of current loop areas after contact separation, case 2

Row	Current rating kA	Time constant ms	Area of 1st major loop kAs	Area of 1st minor loop KAs	Area of 2nd major loop kAs	Total area kAs
1	63	45	0,003	0,250	0,893	1,146
2	50	60	0,007	0,148	0,802	0,957
3	50	75	0,012	0,115	0,875	1,002
4	50	90	0,016	0,093	0,933	1,043
5	50	120	0,023	0,065	1,019	1,108
6	50	80	0,013	0,107	0,896	1,016
7	40	120	0,019	0,052	0,815	0,886

Particular points of Table 8:

a) Row 1 contains the reference values for 50 Hz, 63 kA rating;

b) In rows 2 and 3 it can be seen that a reduction of one step in the R 10 series will cover all cases for τ = 60 - 75 ms;

c) Row 4 shows that for τ = 90 ms the value for the 2nd major loop area exceeds the reference value of 1;

d) In row 5 the rating is still 50 kA but the time constant has been further increased to 120 ms. The area of the major loop has increased even more;

e) The result of the case considered in row 6 is slightly different than the 60 Hz case in that the major loop area slightly exceeds the reference value 1. This 0,3 % difference shows that τ = 80 ms may be very close to the limit of circuit-breaker performance with a reduction of one step in the R 10 series;

f) The case considered in row 7 shows that a reduction by two steps in the R 10 series of the circuit-breaker rating easily covers the requirements for a 120 ms system time constant. However, the additional caution given in comment g) of case 1 applies here also.

From the above it can be seen that considerations are similar for both 50 and 60 Hz cases. The assumption is that the interruption occurs at the end of a major loop of current. If the area of the major loop is exceeded then the probability of an unsuccessful interruption is high. Again de-rating the circuit-breaker 1 step in the R10 series with one level increase in time constant would be satisfactory.

9.4.3 Case 3

In Cases 1 and 2 it was shown that when the current level was reduced one step in the R 10 series the total area of the reference or base case was not exceeded for any dc time constant including 120 ms. It is clear that the basis of comparison must be the area of the major loop of current immediately prior to interruption.

IEC62271-308 recommends a simple way to do the evaluation. It suggests multiplying the major loop amplitude by the loop duration to obtain a representative area for comparison.

Table 9 gives the results of the calculations for the different 60 Hz characteristics for interruption at the end of a major loop.

Table 9 – 60 Hz comparison of integral method to the method of IEC 62271-100

Row	Current rating kA	Time constant ms	Area of major loop	Peak of major loop I kA	Loop duration ms	$I \times t$ kAs	Ratio area of major loop	Ratio area $I \times t$	% difference to integral
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	63	45	0,8058	124,42	10,52	1,3089	1	1	-
2	50	60	0,7182	106,00	11,13	1,1798	0,8913	0,9014	1,13
3	50	75	0,7778	111,49	11,60	1,2933	0,9653	0,9881	2,36
4	50	90	0,8240	115,23	11,97	1,3793	1,0226	1,0538	3,06
5	50	120	0,8905	120,68	12,52	1,5109	1,1051	1,1543	4,45
6	50	80	0,7944	112,73	11,73	1,3223	0,9859	1,0102	2,46
7	40	120	0,7124	96,55	12,52	1,2088	0,8841	0,9235	4,46

The ratio area of column (8) is derived from column 4 by division by 0,8058 and the ratio area of column (9) from division of column (7) by 1,3089.

Particular points of Table 9:

a) The contact parting times of the circuit-breakers were adjusted to obtain interruption at the end of a major loop of current;

b) Row 6 shows that with a one step reduction in the R10 rating series for a d.c. time constant of 80 ms is near the reference area;

c) Rows 4 and 5 again by the ratios show that the rating capability with these time constants has been exceeded;

d) Table 9 clearly shows in the last column that as the time constant increases the error in area also increases.

9.4.4 Case 4

Table 10 gives the results of the calculations for the different 50 Hz characteristics for interruption at the end of a major loop of current.

Table 10 - 50 Hz comparison of integral method to the method of IEC 62271-100

Row	Current rating kA	Time constant ms	Area of 2nd major loop	Major loop amplitude kA	Loop duration ms	$I \times t$	Ratio area base case integral	Ratio area I×t	% difference to integral
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	63	45	0,8932	118,45	12,17	1,4415	1	1	
2	50	60	0,8020	101,46	12,89	1,3078	0,8979	0,9072	1,04
3	50	75	0,8752	107,03	13,46	1,4406	0,9798	0,9994	2,00
4	50	90	0,9333	111,29	13,92	1,5492	1,0449	1,0747	2,85
5	50	120	1,0192	117,33	14,61	1,7142	1,1411	1,1892	4,22
6	50	80	0,8960	108,57	13,54	1,4700	1,0031	1,0198	1,66
7	40	120	0,8153	93,86	14,61	1,3713	0,9128	0,9513	4,22
The ratio area of column (8) is derived from column 4 by division by 0,8932 and the ratio area of column (9) from division of column (7) by 1,4415.									

Particular points of Table 10:

a) Row one is the reference case;

Row 6 shows that by comparing the area of the major current loop, a d.c. time constant of 80 ms on a 50 Hz system is the limit for applications using a one step reduction in the R10 series;

In rows 2 through 7 the product $I \times t$ is compared to the integral method for determining the area as explained in IEC 62271-308, for the purpose of comparing test currents, amplitudes and d.c. time constant for equivalence;

Rows 2 through 7 show that as the d.c. time constant increases, the difference between the two methods also increases;

With a difference of less than 5 % for a time constant variation from 45 ms to 120 ms shows that the simpler method is sufficient to adjust test circuits etc. to obtain the required results.

9.4.5 Discussion

It is believed that the above analysis is conservative since it was done on the basis of no a.c. decrement. This is unlikely in applications requiring full nameplate rating of the circuit-breaker. The method of analysis while detailed in nature is not difficult to do. For accuracy in the integration process it is important that time of the current zero or the change from +/- sign be determined with a good degree of accuracy. For this investigation the calculated current crossing time was calculated to seven decimals. This is needed to develop di/dt information if required. It must also be recognized that this investigation is only addressing the three-phase fault case where one of the phases will always be fully offset. It is the resulting current from that case that is being compared. The fault current that may occur in the other phases while not insignificant will generally be less.

This investigation supports the recommendation that if d.c. time constants greater than 45 ms. are encountered on a system, the selection of a circuit-breaker rated one step up in the R10 series above the expected system fault current for d.c. time constants up to 75 ms should be satisfactory. While the number of cases investigated is limited the method can be applied to almost any combination of three-phase fault current and accompanying d.c. time constant as a predictor of the maximum amount and total amount of energy involved.

Also see Figure 8 and Figure 9 giving selected plots for Case 1 and Case 2 of the current with different d.c. time constants for both 60 and 50 Hz respectively. An examination of the figures suggests that it is also possible to use this method to evaluate different test combinations. For example one could use it to evaluate a test current at 50 Hz to show equivalence to a test current at 60 Hz. Since most such tests will be done using synthetic circuits the di/dt can be adjusted to the correct value at the time of interruption. By varying the amplitude of the current the arc energy can be adjusted to be equivalent. This does become more complicated though because in the end it may be circuit-breaker design dependent. For the circuit-breaker manufacturer that knows the interrupting characteristics of his circuit-breaker this method is still a useful tool for evaluation. An example is an examination of the differences between test currents for 50 Hz, 45 kA and τ = 45 ms and 60 Hz, 40 kA and τ = 90 ms. To help keep it simple, the same assumptions for circuit-breaker contact part times as used in the earlier examples for 50 Hz and 60 Hz will be used. Another assumption is that interruption will take place at the nearest current zero after the requirements for arcing time and relay time have been satisfied. The results are the following:

Table 11 – Tests with different currents, frequency and time constant

Current Rating kA	**Time Constant** ms	**Area of 1st Loop** kAs	**Area of 2nd Loop** kAs	**Area of 3rd Loop** kAs	**Total Area** kAs	**Frequency** Hz
45	45	Major: 0,002	Minor: 0,178	Major: 0,638	0,818	50
40	90	Minor: 0,014	Major: 0,659	Minor: 0,081	0,754	60

See Figure 10 for a plot of this data. As can be seen, the total area for the interruption process for the 60 Hz case is less, but the area of the major loop is greater. Since some circuit-breaker designs are sensitive to this, the current in the 50 Hz case should be increased to make the test equivalent. If the current for the 50 Hz test is increased to 46,5 kA, the area of the major loop is 0,659 kAs, which is virtually identical to the area of the 60 Hz major loop. The choice of how much to increase the current was made by multiplying the 50 Hz current by the ratio of the areas of the major loops.

IEC 62271-100 recognizes the problems associated with testing circuit-breakers with different d.c. time constants. It is fundamental that the circuit-breaker sees the correct prospective di/dt at the time of interruption. As mentioned earlier if synthetic test are conducted this can be adjusted to the correct value. If direct tests are used the current level is adjusted to have the correct di/dt at the time of interruption. One fundamental consideration that must be accounted for is the d.c. time constant of the test station whether direct or synthetic test are used. The effective energy level or area under the current loop can be adjusted by selecting the initiation point of the current relative to the contact parting time of the circuit-breaker or by adjusting the current level or a combination of both to obtain the correct asymmetrical current. This may apply to the final loop of current before interruption. The energy level can be adjusted for the arcing period based on analysis. The methods described can be used to evaluate the test currents to obtain the correct values.

9.5 Conclusions

a) A mathematical method has been introduced for comparison of circuit-breaker duty for different X/R ratios or d.c. time constants;

b) Based on this work a circuit-breaker applied at an interrupting current level one step below the circuit-breaker rating in the R10 series will be satisfactory for a X/R ratio or time constant one step above the standard test value of 45 ms;

c) This evaluation showed, for the limited cases studied, that the one step reduction in the R10 series covered applications up through a d.c. time constant of 75 ms;

d) This method can be used to evaluate equivalence of tests done at 50 Hz at one time constant to cover an application at 60 Hz and a different time constant;

e) This method can be used to check tolerance of applied test currents for compliance with standards for various test arrangements;

f) The method can be used in a testing laboratory in evaluating test circuits;

g) The application engineer needs to determine the actual expected fault current including a.c. and d.c. decrement at the system point of interest to determine the required circuit-breaker rating. In some cases the a.c. decrement can be substantial and may offset the need for a higher rated breaker based on the d.c. requirements alone.

9.6 References

[1] IEC 62271-100, High voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers

[2] IEEE Standard C37.013-1997: Standard for High-Voltage Generator Circuit-Breakers Rated on a Symmetrical Current Basis

[3] IEEE Standard C37.010, 1999: IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

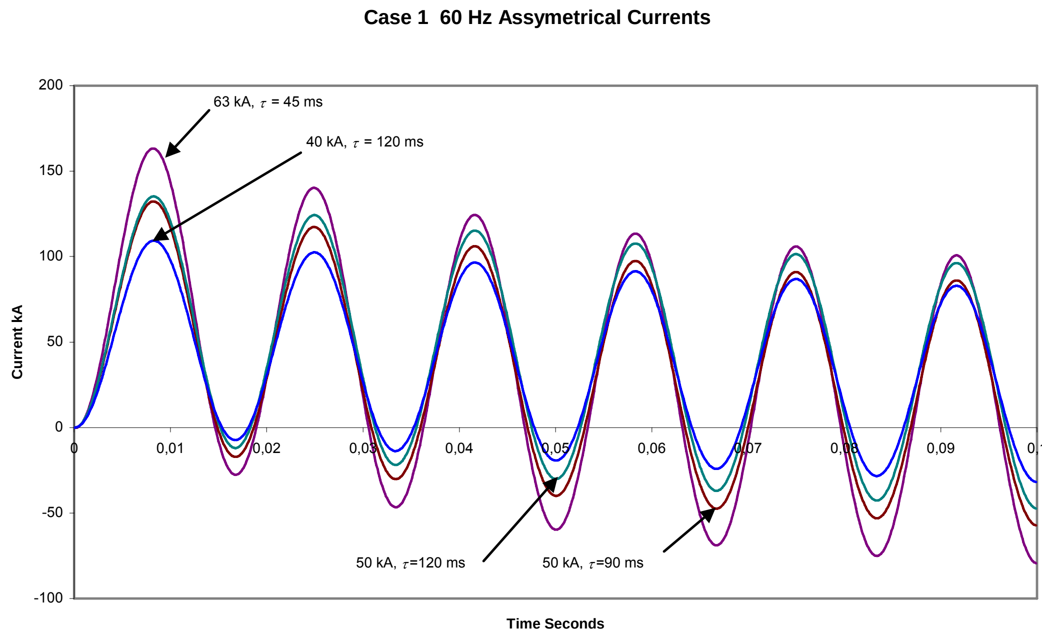


Figure 8 – Plot of 60 Hz currents with indicated d.c. time constants

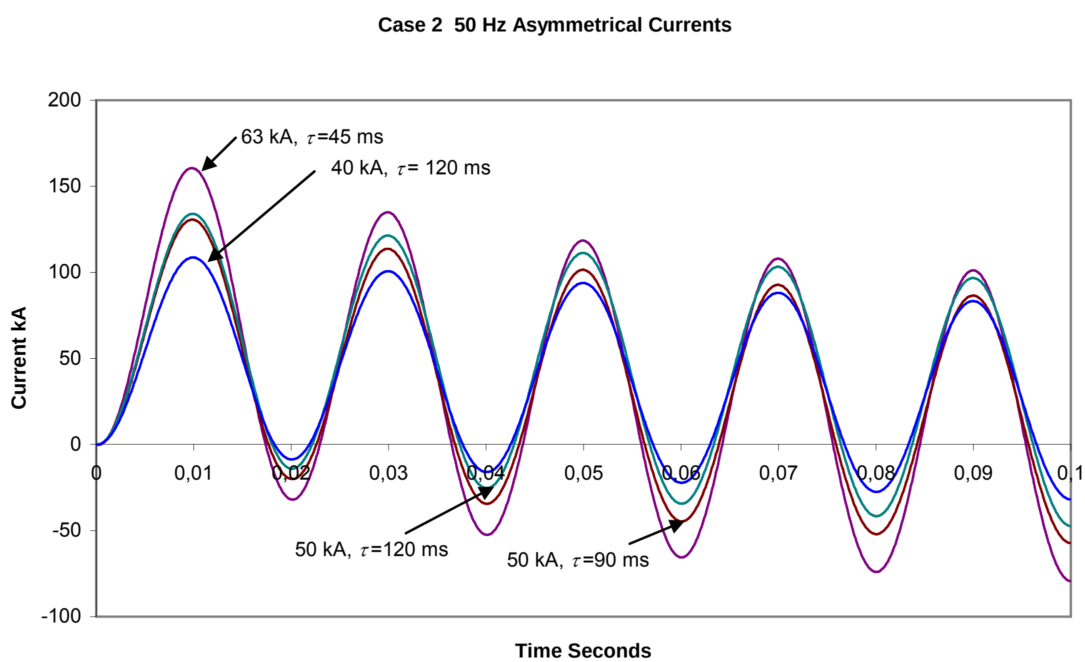


Figure 9 – Plot of 50 Hz currents with indicated d.c. time constants

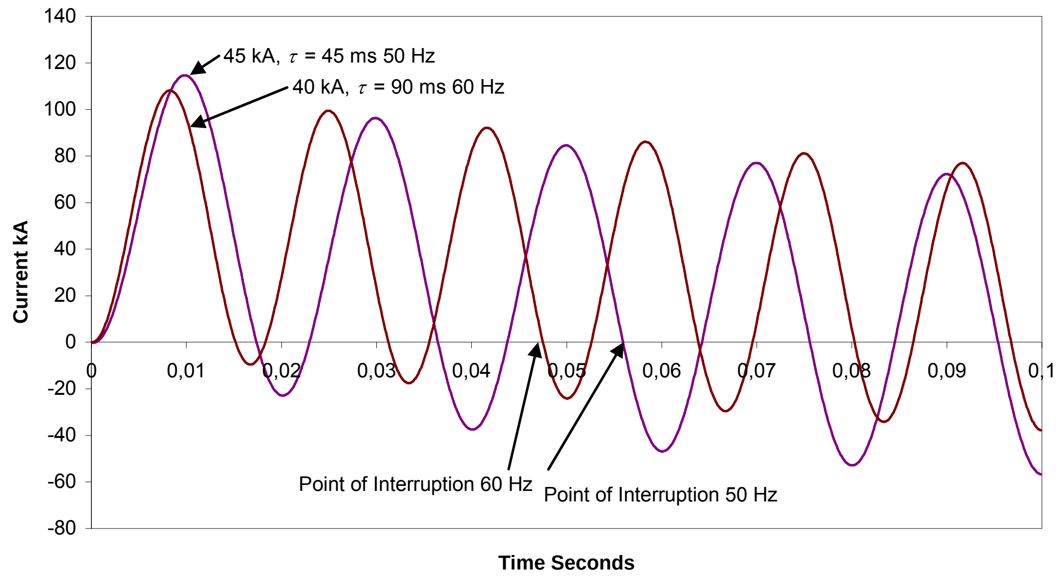


Figure 10 – Plot of 45 kA, 50 Hz vs. 40 kA, 60 Hz with indicated time constants

Appendix A

List of current zero times in ms after 30 ms

Use of the Tables A.1 and A.2:

To determine the duration in ms of any listed current loop, subtract the beginning time for the loop of interest (Table A.1 for 60 Hz and Table A.2 for 50 Hz) from the next listed loop reducing the next listed loop time by 1 in the last given digit.

Example: To determine the duration for 60 Hz, τ = 45 ms major loop that begins at 36,27189 ms:

Duration = 46,79179 – 36,27189 which is 10,5199 ms.

Since the zero crossings are known the di/dt can be calculated by solving the following equation:

$$i = i_{\text{interest}} \sqrt{2} \left(\mathrm{e}^{-\frac{t}{\tau}} - \cos \omega t \right)$$

for the time interval 1 ms prior to the zero crossing.

Table A.1 – 60 Hz, τ = 45 ms – 120 ms

60 Hz						
Start of Loop	τ = 45 ms	τ = 60 ms	τ = 75 ms	τ = 90 ms	τ = 105 ms	τ = 120 ms
Minor -	30,57668	30,86644	31,08127	31,24833	31,38295	31,49439
Major +	36,27189	35,95778	35,72247	35,53898	35,39119	35,26905
Minor -	46,79180	47,08991	47,32160	47,50685	47,65885	47,78631
Major +	53,34279	53,03691	52,79417	52,59825	52,43679	52,30118
Minor -	63,15857	63,44106	63,67276	63,86397	64,02413	64,16037
Major +	70,27267	69,99325	69,75761	69,56041	69,39397	69,25179

Table A.2 – 50 Hz, τ = 45 ms – 120 ms

50 Hz						
Start of Loop	τ = 45 ms	τ = 60 ms	τ = 75 ms	τ = 90 ms	τ = 105 ms	τ = 120 ms
Minor -	36,46687	36,82089	37,08780	37,29571	37,46767	37,60923
Major +	43,76575	43,38735	43,09680	42,86695	42,68009	42,52464
Minor -	55,93170	56,28013	56,55900	56,78591	56,97428	57,13352
Major +	64,22868	63,87931	63,59106	63,35299	63,15387	62,98485
Minor -	75,59678	75,91061	76,17954	76,40730	76,60138	76,76845
Major +	84,51142	84,20971	83,94119	83,70913	83,50913	83,33576

Appendix B

Explanatory note regarding the d.c. component of the rated short-circuit breaking current

B.1 General

A time constant of 45 ms is adequate for the majority of actual cases. Special case time constants, related to the rated voltage of the circuit-breaker, shall cover such cases where the standard time constant 45 ms is not sufficient. This may apply, for example, to systems with very high rated voltage (for example 800 kV systems with higher X/R ratio for lines), to some medium voltage systems with radial structure or to any systems with particular system structure or line characteristics. Special case time constants have been defined in 4.101.2 of IEC 62271-100 taking into account the results of the survey by CIGRE WG13.04 [B.1].

When specifying a special case time constant, the following considerations should be taken into account:

a) The time constants referred to in this standard are only valid for three-phase fault currents. The single-phase to earth short-circuit time constant is lower than that for three-phase fault currents.

b) For maximum asymmetrical current, the initiation of the short-circuit current has to take place at system voltage zero in at least one phase.

c) The time constant is related to the maximum rated short-circuit current of the circuit-breaker. If, for example, higher time constants than 45 ms are expected but with a short-circuit current lower than rated, such a case may be covered by the asymmetrical rated short-circuit current test using a 45 ms time constant.

d) The time constant of a complete system is a time-dependent parameter considered to be an equivalent constant derived from the decay of the short-circuit currents in the various branches of that system and is not a real, single time constant.

e) Various methods for the calculation of the d.c. time constant are in use, the results of which may differ considerably. Caution should be taken in choosing the right method.

f) When choosing a special case time constant, it has to be kept in mind, that the circuit-breaker is stressed by the asymmetrical current after contact separation. The time instant of contact separation corresponds to the opening time of the circuit-breaker and the reaction time of the protection relay. In this standard this relay time is one half-cycle of power frequency. If the protection time is longer this should be taken into account.

g) The choice of a single special case value of the d.c. time constant minimises the number of tests required to demonstrate the capability of the equipment. However, at present no specific equivalence criteria nor testing method can be given to demonstrate the validity of a test carried out at a rated short-circuit current, with its associated rated d.c. time constant, for a different rated short-circuit current with its associated time constant. For example, a test carried out on a circuit-breaker at 63 kA with a d.c. time constant of 45 ms does not automatically cover the requirements for demonstrating a rating of 50 kA with a d.c. time constant of 60 ms.

   Nevertheless, some general important aspects can be considered. The parameters stated below have to be examined carefully in relation to the interrupting technology used:

   1) amplitude of the last current loop before interruption;

   2) duration of the last current loop before interruption;

   3) arcing time window;

   4) arc energy;

5) DC component of the short-circuit current at the instant of contact separation;

6) di/dt at current interruption;

7) TRV peak voltage u_c and first reference voltage u_1, as applicable.

B2 References

[B.1] Electra, No. 173, August 1997, pp 19-31, Specified Time Constants for Testing Asymmetric Current Capability of Switchgear

10 Interruption of currents with delayed zero crossings

This chapter does not cover generator circuit-breakers as they are not in the scope of IEC 62271-100, The circuit-breakers referred to in this chapter are actually high-voltage or medium-voltage circuit-breakers either located on the high-voltage side of the step-up transformer (e.g. as shown in Figure 11) but close to generation, or controlling networks with a high density of generation and large motor loads (e.g. as shown in Figure 23).

An example of the former is the high-voltage circuit-breaker in the connection between a power plant and the high-voltage network (circuit-breaker a_1 in Figure 11). Examples of the latter can be found on off-shore oil platforms, in the auxiliary networks of large power plants, or in certain industrial sites.

The intention of this chapter is to show that it can be determined by calculation whether a circuit-breaker can interrupt currents with delayed zero crossings under given circumstances provided that the performance of that circuit-breaker has been tested in a circuit with currents of more than 100 % asymmetry.

10.1 Faults close to major generation

All circuit-breakers manufactured today are alternating current circuit-breakers, i.e. circuit-breakers that need current zeros to interrupt. However, there are occasions when the fault current does not have current zeros: how can today's SF_6 circuit-breakers manage such situations?

10.1.1 General

Under certain conditions faults occurring close to a power station may lead to the generator currents not passing through zero. Since circuit-breakers can only clear at a current zero this means that such currents could not be interrupted immediately and interruption would be delayed until current zeros occurred due to the d.c. component's decay. In actual fact, however, an arc is drawn between the opening circuit-breaker contacts with the effect that the d.c. components decay much more quickly. Considerable significance is therefore attached to the magnitude and variation of the arc voltage, the intensity of the gas flow and the design of the arc quenching arrangement. The arc drawn between the opening contacts may be regarded as a non-linear resistance which adds to the ohmic resistances of the other circuit elements and which contributes to the reduction of the d.c. time constant of the fault current, whereas the a.c. component remains unaffected.

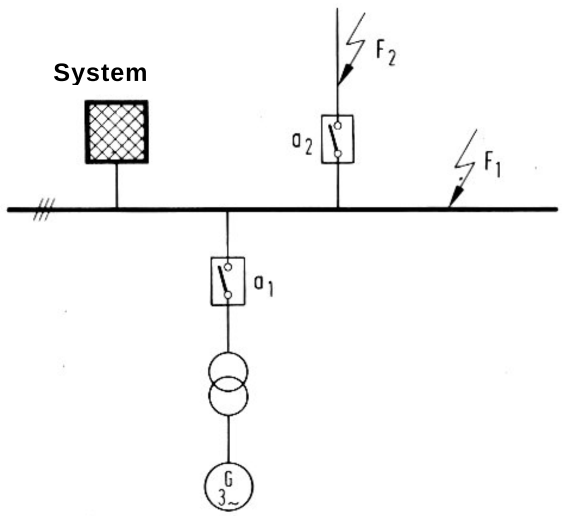
With regard to the degree of fault current asymmetry the theoretical worst case condition is a non-simultaneous unearthed fault. As an example this fault can be a line-to-line short-circuit at voltage zero across two phases which after 90° becomes a three-phase fault at line-to-earth zero voltage in the third phase. This non-simultaneous fault inception produces the theoretically highest d.c. component of 136,6 percent, i.e. it is 36,6 % higher than that of a simultaneous three-phase fault at line-to-earth voltage zero.

10.1.2 Fault location

The conditions for the occurrence of fully asymmetrical fault currents are closely linked to the resulting time constant of the d.c. component $\tau = L/R$, i.e. mainly to the ohmic resistance of the short-circuit path. Therefore, to be able to asses the interrupting capability of circuit-breakers in this particular case, only fault currents supplied by generators which – together with their transformers – account for the smallest X/R ratios, should be taken into consideration.

In case of a fault which is being fed from a generator and also from the network via a transmission line the total fault current is not likely to be fully asymmetric because of the relatively high ohmic resistance of the line.

In the basic circuit diagram in Figure 11 only faults at location F_1, which circuit-breaker a_1 has to interrupt, should therefore be taken into account. Fault currents at location F_2 with its circuit-breaker a_2 are subject to normal current zeros.



Key

F_1, F_2: Fault locations

a_1, a_2: Circuit-breakers

Figure 11 - Power plant substation

10.1.3 Effect of the generator operating conditions

10.1.3.1 Underexcited operation of the generator

With respect to current asymmetry the maximum stress on the circuit-breaker is determined by the generator loading as well as by the particular instant of fault inception. In underexcited operation, when the generator produces active power and consumes reactive power, not only does the initial value of the d.c. component becomes larger than that of the a.c. component, but the time constants and reactances of the generator transverse axis, which are more unfavourable than those of the longitudinal axis, also affect the variation of the a.c. component.

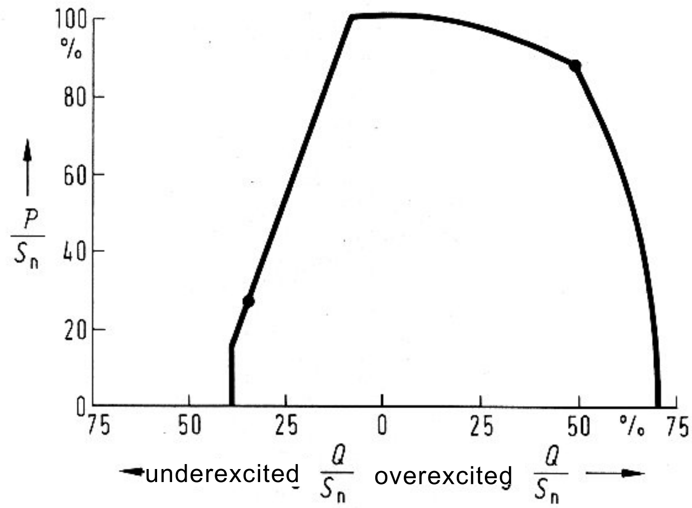
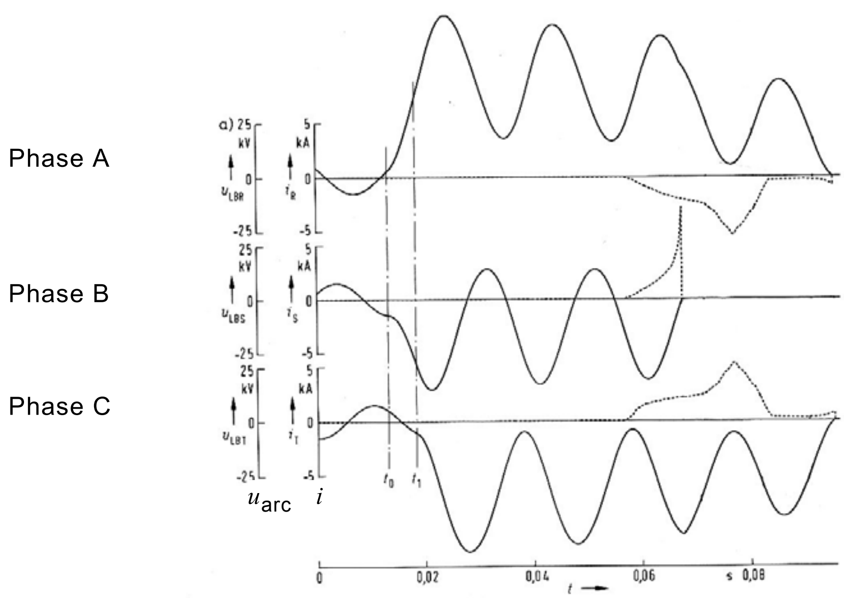


Figure 12 - Performance chart (power characteristic) of a large generator



Key

t_0: Two-phase fault at phase-to-phase voltage zero

t_1: transition to three-phase fault at third phase voltage zero

Figure 13 - Circuit-breaker currents i and arc voltages u_{arc} in case of a three-phase fault following underexcited operation: Non-simultaneous fault inception

For a generator taken as an example an initial load of P = 30 % and Q = -35 % in accordance with the performance chart in Figure 12 was found to be particularly critical.

Calculated currents and arc-voltages for non-simultaneous and simultaneous unearthed fault inception under these conditions are shown in Figure 13 and Figure 14. As there is no arc voltage involved during the first 55 ms these currents (at 50 Hz) can be considered inherent for the initial 55 ms.

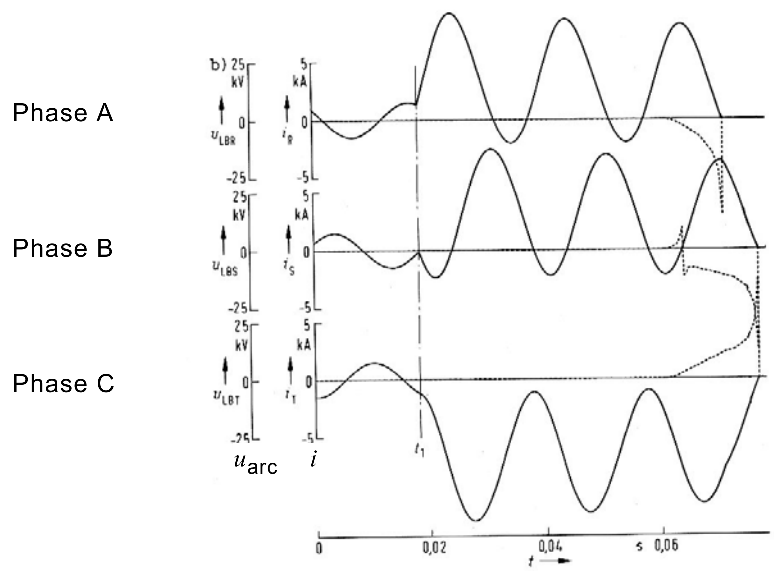


Figure 14 - Circuit-breaker currents *i* and arc voltages u_{arc} in case of a three-phase fault following underexcited operation: Simultaneous fault inception at third phase voltage zero

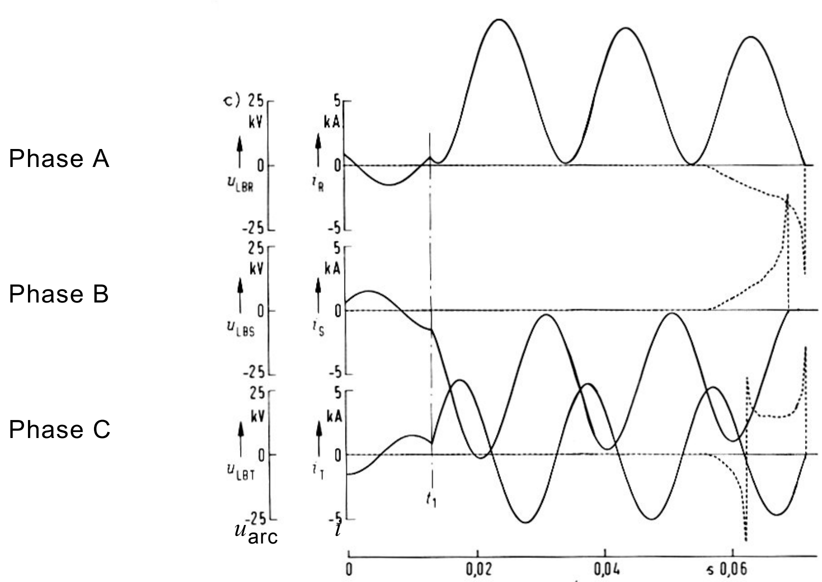


Figure 15 – Circuit-breaker currents *i* and arc voltages u_{arc} in case of a three-phase fault following underexcited operation: Simultaneous fault inception at third phase voltage crest

In Figure 13 the initially two-phase fault occurred across the upper two phases at time t_0. The third phase was subjected to the now three-phase fault at time t_1. It can be seen that a further d.c. component is added in the first phase to the d.c. component of the two-phase fault current resulting in an asymmetry of the current in this phase of more than 100 %.

In the second phase current zeros continue to occur, while the d.c. component in the third phase is, also, above 100 %, but not as high as in the first phase.

For a given SF_6 circuit-breaker, the arc voltage of which has been determined experimentally, it has been assumed that an effective arc voltage appears between the opening contacts 55 ms after fault inception. This takes into account the time until contact separation and some milliseconds for the development of the full gas flow. The current in the second phase is interrupted at the next current zero. Consequently, a phase shift takes place in the a.c. and in the d.c. components in the other phases: the d.c. component in the first phase decreases, while it increases in the third phase there leading to an even higher current offset. However, due to the effect of the arc voltage, which acts as an additional resistance R_a and thus reduces the momentary value of the d.c. time constant to $\tau = L/(R + R_a)$, the currents are forced through zero in the first and third phase, as well, and are interrupted.

Figure 14 and Figure 15 show simultaneous unearthed faults which occur at time t_1. The d.c. components are less pronounced and the interruption takes a similar course as described for Figure 13.

The arc voltage will also cause the fault currents to pass through zero in the event of a generator transformer fault (Figure 16) but with the conditions otherwise the same as in Figure 13.

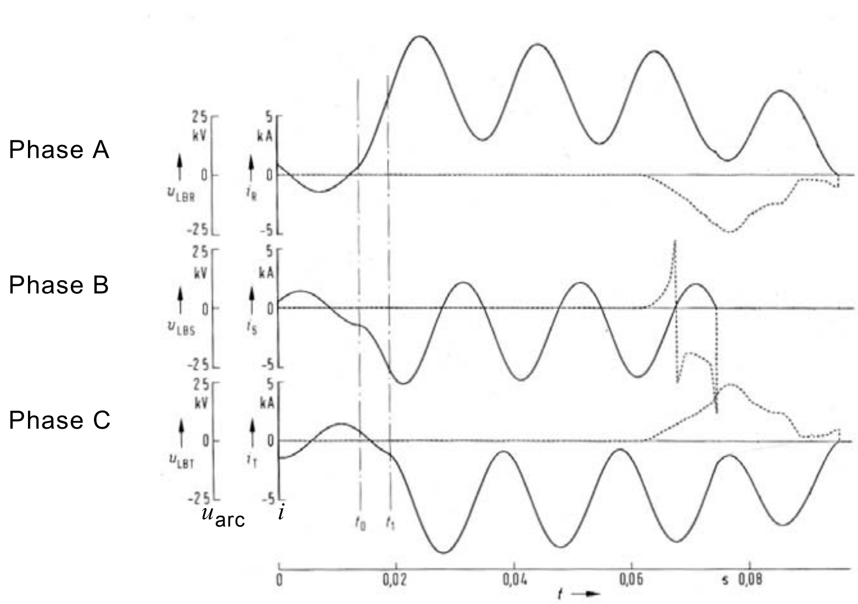


Figure 16 – Circuit-breaker currents *i* and arc voltages u_{arc} under conditions of a non-simultaneous three-phase fault, underexcited operation and failure of a generator transformer

10.1.3.2 Overexcited operation of the generator

Fault clearance following overexcited loading of the generator, i.e. active-power and reactive-power output, subjects the circuit-breaker to lower stresses (Figure 17). The maximum displacement of the currents from the zero line under fault conditions following full load operation is much smaller than that of the currents due to underexcited operation (Figure 13).

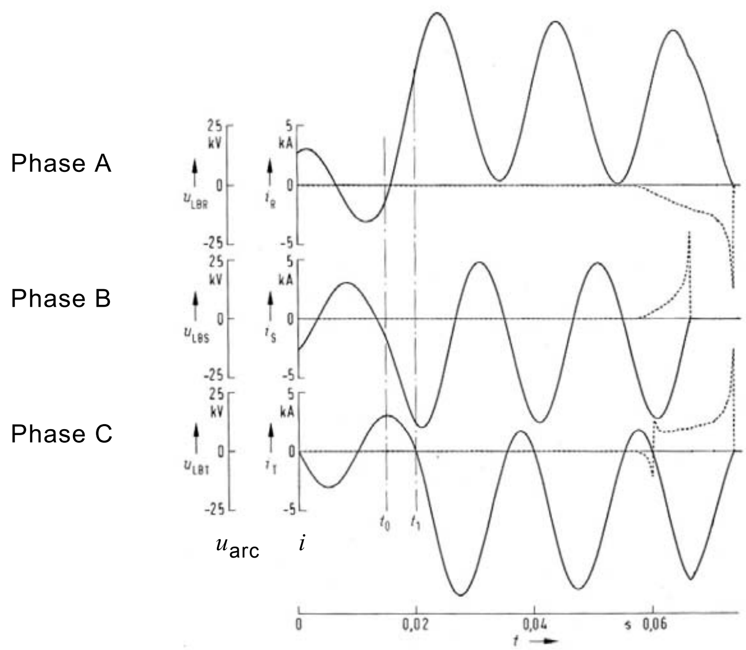


Figure 17 – Circuit-breaker currents *i* and arc voltages u_{arc} under conditions of a non-simultaneous three-phase fault following full load operation

10.1.3.3 No-load operation of the generator

The calculated currents and arc voltages due to a non-simultaneous fault developing from no-load operation of the generator are shown in Figure 18. As in case of a fault following full load operation (Figure 17) the displacement of the currents from the zero line is smaller than for underexcited operation.

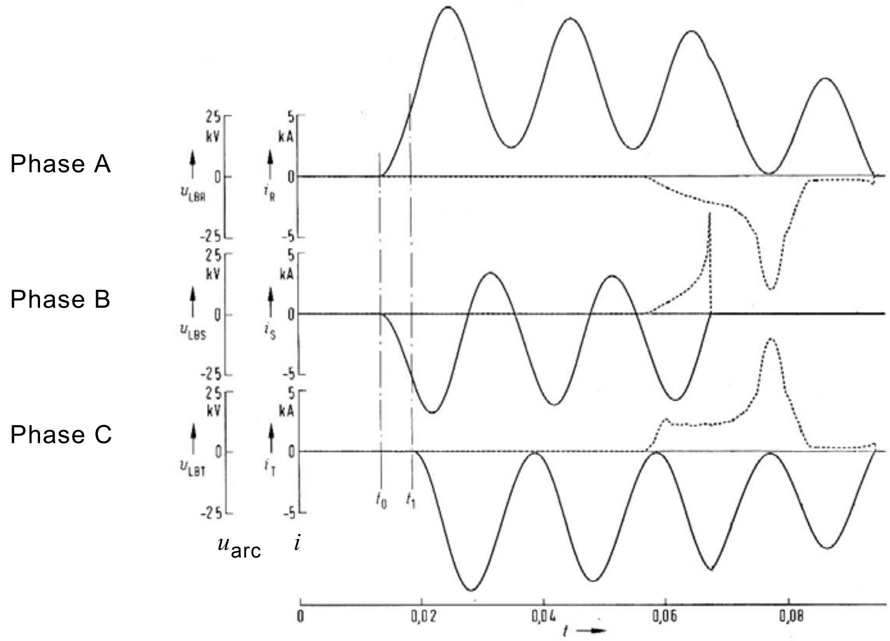


Figure 18 – Circuit-breaker currents *i* and arc voltages u_{arc} under conditions of a non-simultaneous three-phase fault following no-load operation

10.1.4 Unsynchronized closing

It can be seen from Figure 19 that not only fault conditions but also attempting to synchronize at an unsuitable differential angle may cause the current zeros to be delayed. Owing to the mean electrical moment which thereby occurs and the resulting speed variation the currents can be constricted to such an extent that they may no longer pass through zero in any of the phases. However, this does not occur until after a prolonged period because of the much higher mechanical time constants. Should the circuit-breaker operate in this constriction range it still can interrupt the current due to the higher arc voltage as shown in Figure 19.

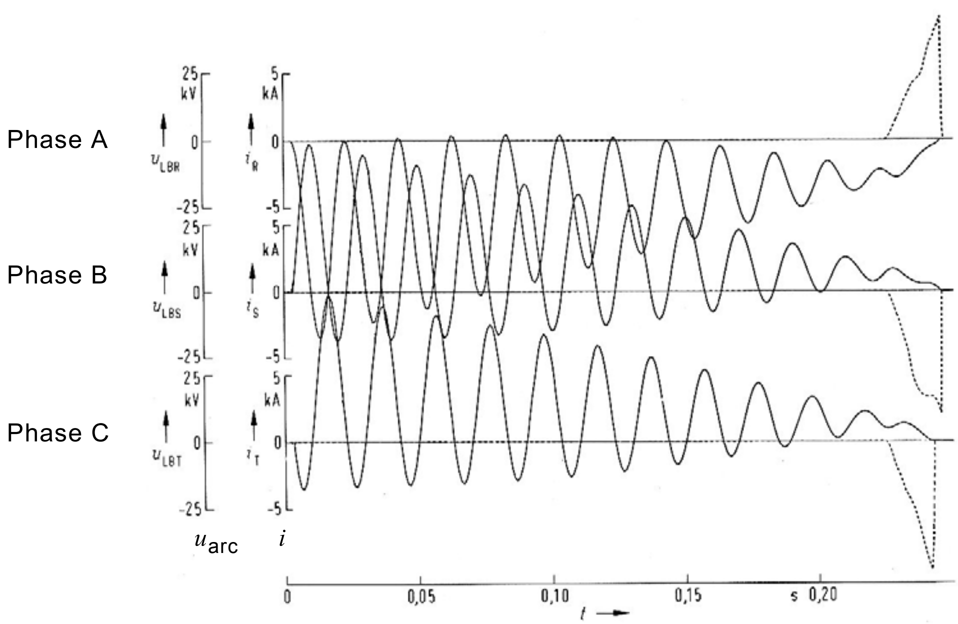


Figure 19 – Circuit-breaker currents i and arc voltages u_{arc} under conditions of unsynchronized closing with 90° differential angle

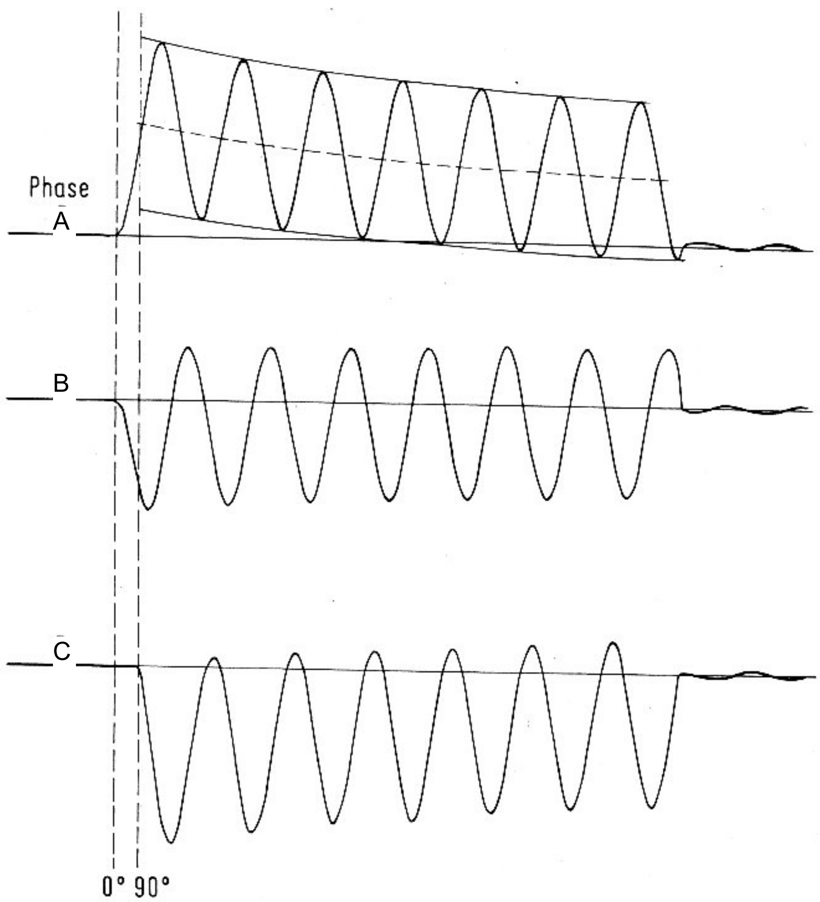
10.1.5 Proof of performance

10.1.5.1 Testing

Normally, testing of a high-voltage circuit-breaker under these conditions can, only, be carried out single-phase, i.e. on the circuit-breaker pole with the highest d.c. component. To produce d.c. components greater than 100 % for several cycles the test circuit must have a high X/R ratio giving a d.c. time constant τ of possibly several hundred ms. The test voltage must be at least as high as the rated phase voltage or in case of unit testing as high as the rated voltage across the most highly stressed interrupter for the first phase-to-clear in an unearthed fault or the last phase-to-clear in an earthed system. The a.c. component of the test current has to cover the a.c. component of the short-circuit current of the generator considering the conditions stated in clauses 10.1.1 and 10.1.2.

In practice the test procedure in order to subject one pole to a short-circuit current with delayed current zeros is as follows (Figure 20, Phase A).

In most cases the tests are made single-pole on one interrupter unit. The first two phases of the test circuit are switched in by a make-switch when their phase-to-phase voltage passes through zero. The third phase is switched in a quarter cycle later. By varying the delay of the making in the third phase the amount of asymmetry of the short-circuit current can be adjusted. Figure 20 shows the oscillogram of the current not affected by the arc, i.e. the inherent current of the test circuit. It can be seen that at the transition to the three-phase circuit a further d.c. component is added to the d.c. component of the two phase current with the effect that the current in phase A is displaced by more than 100 %. The short-circuit generators should not be superexcited to delay the current zero by several cycles due to the decaying a.c. component.



Example:

Test voltage: 70 kV — 1st current minimum: 850 A

Test current: a.c. component: 2,63 kA r.m.s. — 2nd current minimum: 450 A

Current peak: 8,5 kA — 3rd current minimum: 260 A

Figure 20 - Prospective (inherent) current

The contacts of the test breaker should be set to part about 1 ms after the initial inception of the current flow. Thus, the test circuit-breaker is subjected to the maximum asymmetrical current after contact separation. The arcing time is then varied systematically in order to determine the minimum and maximum times for each a.c. current and voltage step.

10.1.5.2 Calculation of the performance of a circuit-breaker

The arc characteristics measured during the tests are converted into a mathematical model in order to obtain details about the interrupting capability of the circuit-breaker in other situations or under the varied fault conditions, respectively. The model must be a true representation of the arc voltage variation from contact separation until arc extinction. The instantaneous values of the currents and corresponding arc voltages, which were taken from actual test oscillograms, produce the distribution of dots shown in Figure 21 together with the mean tolerance band. The wide variation of the readings results from the instable and rather inconsistent arc behaviour.

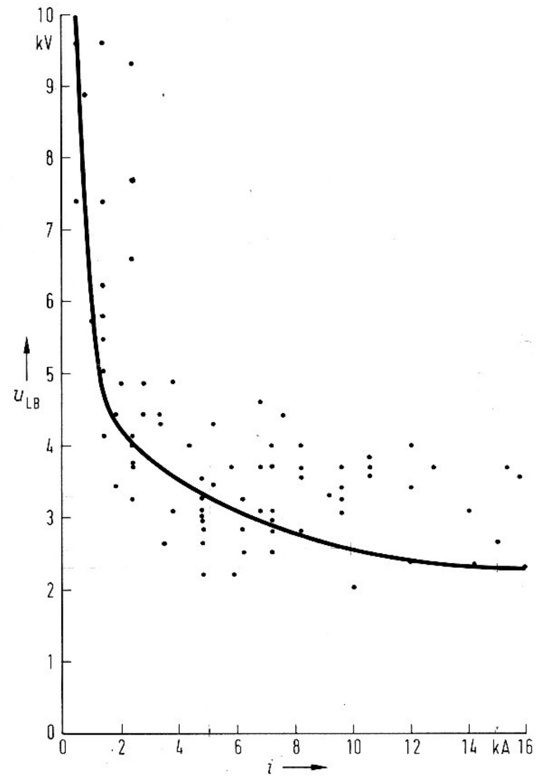


Figure 21 - Arc current-voltage characteristic of a high voltage circuit-breaker interrupter

In addition to the voltage-current characteristic of the arc, the variation of the gas pressure in the arcing chamber, the extension of the arc by the gas flow and the contact distance which rises with the arcing time must be taken into account. These circuit-breaker characteristics can be expressed mathematically by a standardized assessment function $e(t)$ with a maximum value of 1 (Figure 22). Strictly speaking this function has no physical significance.

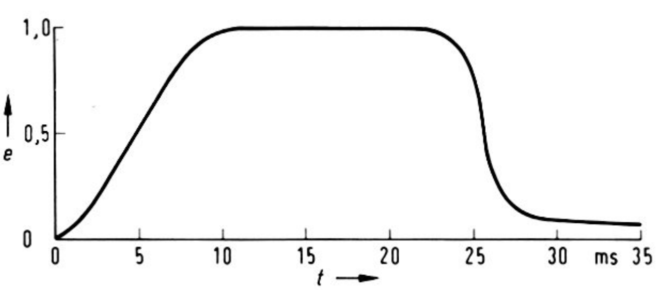


Figure 22 - Assessment function $e(t)$

The total function of the arc voltage – as a function of time, the circuit-breaker characteristics and the instantaneous current value – is obtained by multiplying the individual functions shown in Figure 21 and Figure 22.

$$u_{\text{arc}}(t,\, i) = u_{\text{arc}}(i) \times e(t)$$

Using this total arc voltage function u_{arc} the arc drawn between the opening contacts may be regarded as a non-linear ohmic resistance which mainly reduces the d.c. time constant of the fault current, while the a.c. component remains unaffected.

Other methods of calculation have also been developed to compare testing and simulation [1] and [2].

10.1.6 Distributed generation and large motors

In distribution voltage systems fault currents with delayed zero crossings may occur either in the proximity of a concentration of generation or when switching-off large high-voltage motors or in a combination of both. Even vacuum circuit-breakers with their relatively low arc voltage may be well suited to clear under these conditions, provided they are designed to withstand the high current peak values associated with such faults. Also, their contact configuration must be able to withstand prolonged arcing. In any case it will be necessary to investigate the conditions of the particular application to determine the actual stress upon the circuit-breaker.

10.1.7 Conditions for fault currents with delayed zeros

In distribution voltage networks with an extremely large concentration of generation and motor load, the probability that short-circuit currents with a d.c. component well above 100 % will occur is even higher than in high voltage systems. The d.c. time constant τ may be in the order of some hundreds of milliseconds. This means the current in at least one phase will have no current zeros for several cycles.

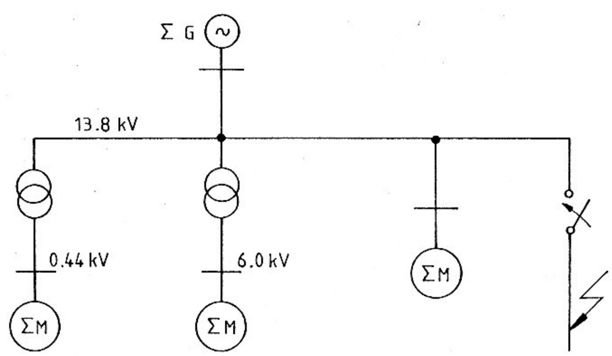
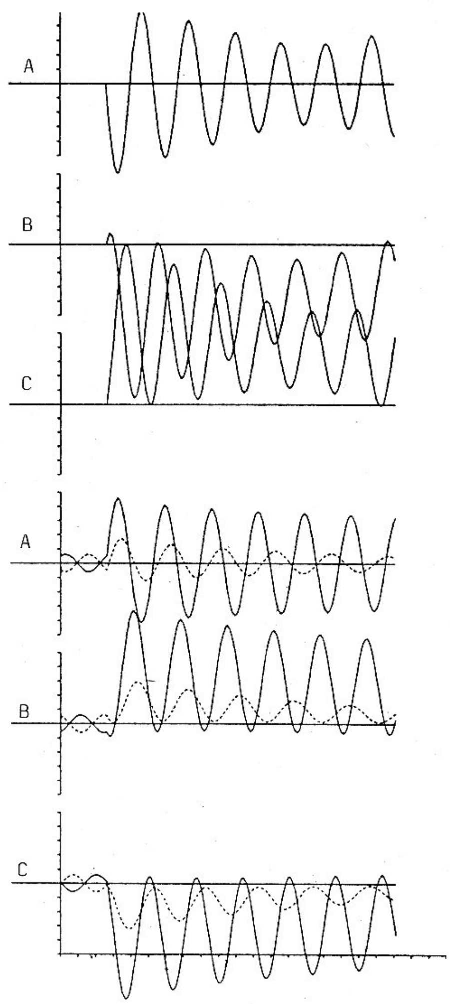


Figure 23 - Network with contribution from generation and large motor load

If large high voltage motors are present short circuits with delayed current zeros will not only occur due to a non-simultaneous fault, but they are even possible in case of a simultaneous (bolted) fault (Figure 23). If there is a fault the motors act as generators and feed back into the system a current with a high d.c. component. As they are slowing down they will gradually become out-of-phase with respect to the feeding system. The frequency of the current generated by the motors will drop below the generator frequency. As Figure 24 shows, even if the short-circuit current from the generators has current zeros the superposition of the current generated by the motors results in a total short-circuit current with delayed current zeros.



Key

Upper traces: Total fault current.

Lower traces:

- solid lines: generator fault current, d.c. time constant τ = 180 ms
- dotted lines: fault current generated by the motor

Figure 24 - Computer simulation of a three-phase simultaneous fault with contribution from generation and large motor load

From Figure 24 it can be determined that the probability of occurrence of a short-circuit current with delayed zeros is higher if the generator short-circuit current has a large d.c. component with a long d.c. time constant. This is the case if the fault location is close to the generators. If generation and motor load are located close to each other, the damping of the short-circuit current d.c. component is particularly low and the conditions assumed in Figure 24 are met. Typical examples are offshore oil platforms where generation and load may be in the order of or even above 50 MVA and the connections are short and industrial plants which may be run in certain parts on their own power supply.

In industrial plants which are fed via transmission lines or cables these lines or cables act as damping elements for the d.c. component, and the resulting total fault current most probably has zeros in all three phases continuously from the fault inception.

10.1.8 Three-phase interruption of currents with delayed zeros

Most distribution class voltage circuit-breakers have a common mechanism which is linked to the three poles via a common shaft. Therefore, all making and breaking operations are carried out three-phase. Accordingly, studies whether such a circuit-breaker is able to interrupt a fault current with delayed zeros must be carried out on a three-phase basis.

The sequence of a three-phase interruption may be shown taking a non-simultaneous fault in an unearthed system as an example. Consequently, the a.c. components and the d.c. components in the three phases add up to zero, respectively.

To cover the extremes it is considered that the short-circuit may occur at voltage zero as well as at voltage crest of one phase. The vector diagrams Figure 25 and Figure 26 show the a.c. and d.c. components of the currents in all phases at inception of the three-phase fault and after the interruption by the first pole-to-clear. The a.c. components of the three-phase current are normalized to 1 p.u. and their decay is neglected in the vector diagrams. Likewise, no decay of the d.c. components is taken into account.

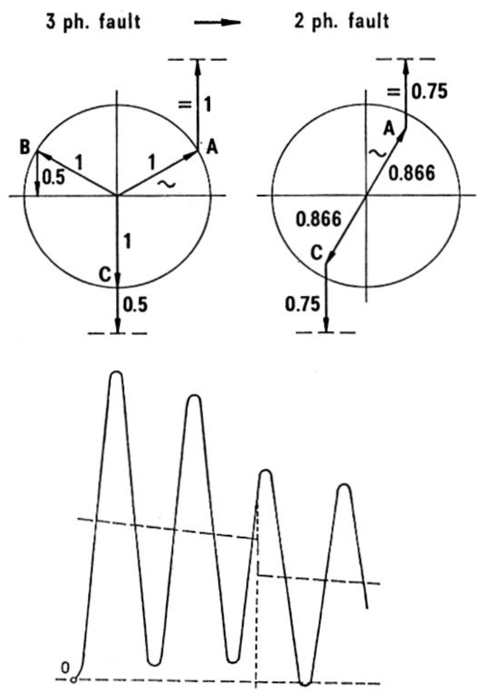


Figure 25 - Short-circuit at voltage zero of phase A (maximum d.c. component in phase A) with transition from three-phase to two-phase fault

If a short-circuit occurs at voltage zero one phase has the maximum possible offset. This is considered to be phase A in Figure 25, with a d.c. component of ±1 p.u. Consequently, the d.c. components in the two other phases are - 0,5 p.u. In these phases there are always current zeros giving the corresponding circuit-breaker poles the possibility to clear. After interruption of the first phase (e.g. by pole B) there is a phase shift in the remaining two phases: their a.c. components become ±0,866 p.u. and their d.c. components ±0,75 p.u. Even the originally fully offset phase will have current zeros now and all circuit-breaker poles are able to clear.

Generally speaking, in case of a fault at voltage zero this phase shift will lead to a reduction of the d.c. component in the most offset last phase. In most cases there will be current zeros now also and the two last-to-clear poles are able to interrupt as well. Even if there are no current zeros immediately after the phase shift the current offset is reduced, leading to current zeros after one or two further cycles.

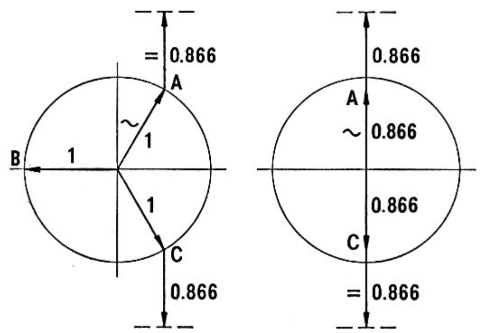


Figure 26 - Short-circuit at voltage crest of phase B (phase B totally symmetrical) and transition from three-phase to two-phase fault

In case of a short-circuit at voltage crest the current in one phase will be totally symmetrical. (phase B in Figure 26). The other two phases then have a d.c. component of ±0,866 p.u. Accordingly, as long as this is a three-phase short-circuit all phases have current zeros. If the symmetrical current in phase B is interrupted first the phase shift will change the a.c. components in the other two phases to ±0,866. The d.c. components in those phases remain unchanged. This means that the a.c. and d.c. components have equal amplitudes and the current will now only touch the zero line.

To determine whether a circuit-breaker is able to clear such a fault, it is therefore important to consider how the a.c. components and the d.c. components develop during the short-circuit. Both decay in a different manner. The a.c. components consist of a subtransient and a transient short-circuit current. While the subtransient short-circuit current decays with a time constant of 20 to 30 ms, the transient time constant may be in the order of several hundred milliseconds, even up to some seconds. The d.c. component has a time constant $\tau = L/R$ which is determined by the reactance and the resistance of the faulted circuit, including the generators, transformers and switchgear. On oil platforms it often has a value between 200 and 300 ms.

Depending on the load conditions of the generators, i.e. on their state of excitation before fault inception, the a.c. component may decay more rapidly than the d.c. component. Especially if the subtransient a.c. short-circuit current is of great significance the amplitude of the a.c. component may have become smaller than that of the d.c. component by the time the first phase is cleared. In that case there will be no current zeros in the one or two more offset last phases. The arc in these two circuit-breaker poles will now have to burn for another one or two cycles. As even the relatively small arc voltage of vacuum circuit-breakers contributes to the reduction of the d.c. time constant, the d.c. components will decrease further and current zeros will occur again giving the circuit-breaker to finally interrupt.

Therefore, of the two conditions of fault inception, the three-phase short-circuit at voltage crest might be considered more severe for three-phase interruption as there may be a possibility for the last poles-to-clear only with prolonged arcing. However, a short-circuit at voltage zero will stress a circuit-breaker with a higher d.c. component and thus with an overall higher current peak. These considerations show that each circuit configuration has to be regarded individually in order to determine the critical stress imposed upon the circuit-breaker. Above all it is necessary to evaluate, at the moment of contact separation, the amplitudes of the a.c. and the d.c. component and their time constants.

10.1.9 Application of distribution voltage class circuit-breakers

As pointed out, already, the application of distribution class voltage circuit-breakers for the clearance of faults with delayed current zeros is based upon the assumption that these circuit-breakers will always interrupt by three-pole operation. Accordingly, all analytical considerations and tests have to be carried out on a three-phase basis.

Although the arc voltage, as for vacuum circuit-breakers, may only be in the order of about 100 V experience shows that it has a non-negligible effect upon the decay of the d.c. component.

When tested according to IEC 62271-100 or IEEE C37.013, the circuit-breaker has to clear a symmetrical short-circuit current or a short-circuit current with a d.c. component of some tens of percent at a moment when the power frequency recovery voltage is at its crest or near to it. This leads to a transient recovery voltage with a relatively high peak value. In case of a short-circuit current with a very high d.c. component the moment of current zero almost coincides with the moment of voltage zero of the power frequency recovery voltage. Thus, the transient recovery voltage stress immediately after current interruption becomes relatively low.

A circuit-breaker suited to clear faults with delayed current zeros must be able to make and withstand very high current amplitudes due to the d.c. components in the order of 130 %. Also, the contacts must be able to withstand thermally arc durations of two or even three cycles and still interrupt a fully offset short-circuit current. Consequently, it is advisable to use in such case a circuit-breaker with a higher short-circuit current rating than that which the particular application suggests.

According to test experience the contacts designed to absorb the energy connected with the breaking of such rated short-circuit current without being overheated are most likely capable to withstand the arc duration required to clear under the conditions of delayed current zeros.

10.1.10 Testing

To demonstrate the capability of distribution voltage class circuit-breakers to withstand and to clear faults with delayed current zeros three phase tests should be carried out in a similar circuit as described in 10.1.5.1. The test circuit parameters (test voltage, frequency, TRV) shall correspond to those rated for a system of the particular application. The tests should cover both conditions as described in 10.1.8:

a) with the maximum d.c. component in one phase, i.e. one phase fully offset, corresponding to a short-circuit occurring at voltage zero;
b) with practical no d.c. component in one phase, i.e. one phase fully symmetrical, corresponding to a short-circuit occurring at voltage crest.

To achieve the maximum offset current with a large d.c. time constant a special sequence has to be chosen in producing a three-phase non-simultaneous short-circuit (see 10.1.5.1). Two phases are switched in when their phase-to-phase voltage passes through zero. The third phase is closed a quarter cycle later. By varying the delay of the making in the third phase the amount of asymmetry of the short-circuit current can be adjusted. The short-circuit generator should not be superexcited.

10.2 References

[1] IEEE Transactions on Power Delivery, vol. 17, N°4, October 2002: Design and Implementation of an SF_6 Interrupting Chamber Applied to low range Generator Circuit

breaker suitable for Interruption of Current having a Non-zero Passage", D. Dufournet – J.M. Willième – G. Montillet.

[2] CIGRE 2002 Paper 13-01: Generator Circuit-breaker; SF6 Breaking Chamber Interruption of Current with non-zero passage – Influence of cable connection on TRV of system-fed faults, D. Dufournet – J.M. Willième

11 Parallel Switching

11.1 Introduction

Parallel switching occurs when two or more circuit-breakers are tripped to interrupt a shared fault current. This is typically the case for such bus arrangements as double breaker, breaker-and-a-half, breaker-and-a-third and ring buses. Ideally, all of the circuit-breakers should interrupt at the same current zero and this would probably be the case if all circuit-breakers were of the same type and technology, and contact parting was simultaneous. In reality, the evolution of circuit-breakers has resulted in different circuit-breaker types and technologies being mixed quite randomly as stations are extended.

The purpose of this chapter is to examine this switching case and to relate it to oil, air-blast, SF_6 and vacuum circuit-breakers operating in parallel in various combinations. Experience indicates that parallel switching is not so much an issue of concern but it is a frequently asked question and the purpose of this chapter is to provide a better understanding of the switching duty. In this context it is important to note that circuit breakers do not have a parallel switching rating but rather a certain inherent capability for the duty. Parallel switching is influenced primarily by circumstances relating to the progressive development of circuit-breakers and their actual application by and under the control of the users. It is therefore a user matter and this chapter provides guidance as to how the user can assess parallel switching with the necessary technical support from the circuit-breaker manufacturers. Note that parallel switching should not be confused with evolving faults, the latter being a different phenomenon.

11.2 Circuit-breaker characteristics

Parallel switching is influenced by the types of circuit-breakers involved and their respective characteristics as follows:

- relative mechanical opening times;
- relative current levels;
- relative arc voltages;
- relative arcing windows;
- system and local impedances;

However, as will become apparent in 11.3, the factors that need to be considered are the relative mechanical opening times, the relative arc voltages and to some degree the system and local impedances. Experience shows that the ranking of mechanical opening times from fastest to slowest most probably is as follows:

a) Air-blast circuit-breakers;
b) SF_6 circuit-breakers;
c) Oil circuit-breakers;
d) Medium voltage circuit-breakers of all types.

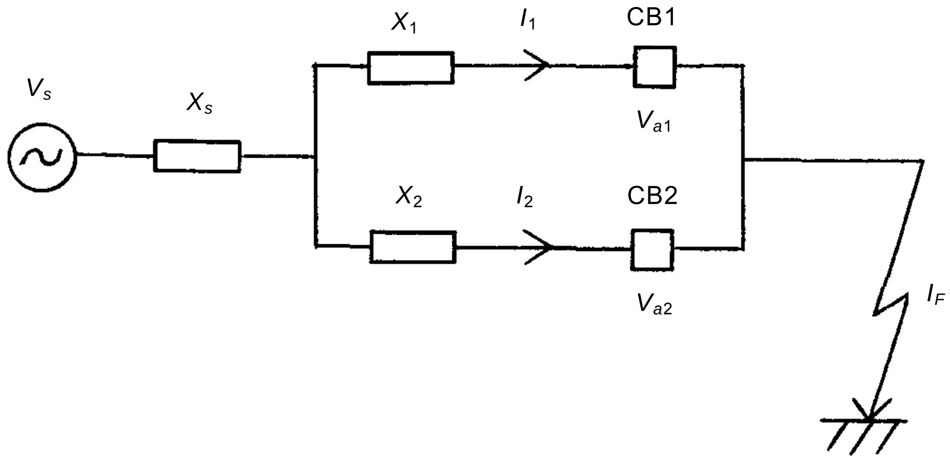
The ranking of arc voltages from highest to lowest is as follows:

a) Air-blast circuit-breakers;
b) Oil circuit-breakers;
c) SF_6 circuit-breakers;
d) Vacuum circuit-breakers.

As to the system and local impedances, the former will dominate and will give the same phase angle for the currents in the two circuit breakers in parallel. The local impedances will determine the current division between the two circuit breakers. If the circuit breakers remain closed that current division will stand; however, once at least one of the circuit breakers contacts part, it is the arc voltage that will dominate in determining the current division and the ultimate outcome.

11.3 Analysis and Rules

The equivalent circuit for parallel switching analysis is shown in Figure 27.



Key

V_s	Source voltage
X_s	Remote source impedance
X_1, X_2	Local impedances
I_F	Fault current
I_1, I_2	Current in circuit-breakers CB1 and CB2
V_{a1}, V_{a2}	Arc voltages of circuit breakers CB1 and CB2

Figure 27 - Equivalent circuit for parallel switching analysis

The system can be treated essentially as a constant current source. Ignoring resistance for simplicity and thinking in terms of absolute values, the following applies:

$$I_F = I_1 + I_2 \qquad (18)$$

and

$$I_1 X_1 + V_{a1} = I_2 X_2 + V_{a2} \qquad (19)$$

assuming that the contacts have parted on both circuit-breakers.

Combining Equations (18) and (19):

$$(I_F - I_2) X_1 - I_2 X_1 = V_{a2} - V_{a1}$$

or

$$I_2(X_1 + X_2) = I_F X_1 + V_{a1} - V_{a2}$$

The condition for I_2 to go to zero, i.e. to commutate to CB1 is:

$$I_F X_1 + V_{a1} - V_{a2} = 0$$

or

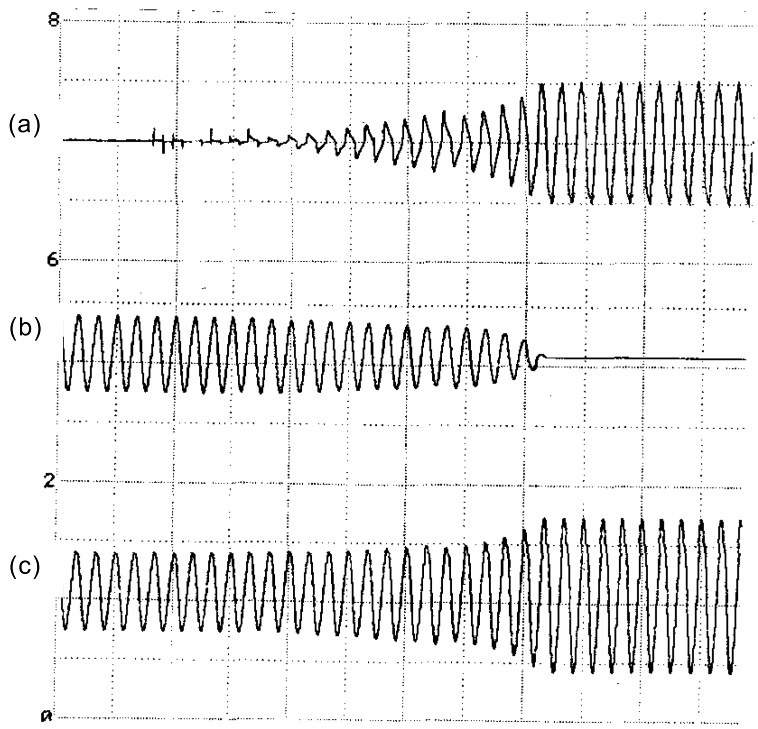
$$V_{a2} = I_F X_1 + V_{a1} \qquad (20)$$

Likewise for I_1 to commutate to CB2, the condition is:

$$V_{a1} = I_F X_2 + V_{a2} \qquad (21)$$

The interpretation of Equations (20) and (21) is that the current will commutate from the first circuit-breaker to achieve an arc voltage equal to the open circuit voltage after commutation or, put more simply, the current will commutate from the circuit-breaker with the highest arc voltage to the circuit-breaker with the lower arc voltage. This is the basic rule of parallel switching.

The rule is illustrated in Figure 28 which shows an actual case of a disconnector being used to parallel switch between two transmission lines. After contract parting, it can be seen that the arc voltage builds as the arc is elongated and the current gradually transfers to the parallel line. The current in the disconnector goes finally to zero when the arc voltage equals the open circuit voltage across the switch. Note that this switching event relies on a natural commutation and thus takes a number of cycles dependent on the series and parallel path impedances. In the case of circuit-breakers, the commutation is forced and rapid, and will take place within one half-cycle.



a) Voltage across disconnector

b) Current in disconnector

c) Current in parallel transmission line

Figure 28 - Parallel switching between transmission lines with disconnector

11.4 Parallel switching in practice

Clearly many parallel switching scenarios are possible in practice. A base case will be considered and then variations will be discussed in relation to this case.

The base case assumes simultaneous contact parting (in reality this may not always be the case particularly in fault events which cause several protection systems to operate) and about equal current in both circuit-breakers. Actual sharing of current in reality is most likely to be reasonably close, say in the 60 % / 40 % range at worst. Table 12 shows the direction of current transfer for the base case (refer to Figure 28) with regard only to the hierarchy of arc voltages and the rule discussed above.

Table 12 - Current transfer direction for parallel circuit breakers with same contact parting instant and based on arc voltage

CB1	Current transfer direction	CB2
Oil	→ ←	Oil
Oil	←	Air Blast
Oil	→	SF_6
Oil	→	Vacuum
Air blast	→ ←	Air blast
Air blast	→	SF_6
Air blast	→	Vacuum
SF_6	→ ←	SF_6
SF_6	→	Vacuum
Vacuum	→ ←	Vacuum

For high-voltage circuit-breakers, the mechanical opening times can vary from 16 ms for air blast and some SF_6 circuit-breakers to about 25 ms for oil circuit-breakers. For medium voltage circuit-breakers, mechanical opening times can be quite long and in the range of 40 to 60 ms. Applying the rule, the following outcomes are probable:

- If the contact parting on the same phase of both circuit-breakers is within the same half-cycle, current will start to transfer from the circuit-breaker that opens first (with reference to Equations (20) and (21), the arc voltage needs only to achieve a voltage equal to the voltage across the parallel local impedance). If the transfer is not complete by the time the contacts part on the second circuit-breaker, then the transfer will be determined by the relative arc voltages.
- If the contact parting of the two circuit-breakers are in consecutive half-cycles, two outcomes are possible. If the contact parting of the first circuit-breaker to open is well prior to the current zero crossing but less than the minimum arcing time, then the current will transfer to the parallel circuit-breaker during the period of significant change of arc voltage at the latest. However, if the contact parting instant of the first circuit-breaker to open is close to the current zero crossing, it may not develop sufficient arc voltage to effect a transfer and the transfer may then be determined by the relative arc voltages once the contacts part on the parallel circuit-breaker.
- For medium voltage circuit-breakers, where the difference in contact parting times can span about one cycle at 50 Hz or more than one cycle at 60 Hz, the above outcomes also apply with the added possibility of two current zeros between the respective contact parting times. In the event of the latter possibility, the current will transfer from the first circuit-breaker to open at the second current zero at the latest.

- In the event of a large current imbalance but dependent on the relative contact parting instants and the circuit-breaker types, the circuit-breaker with the lower current will probably commutate its current to the other circuit-breaker. The reason for this is the negative characteristic of the arc voltage. An example of such a characteristic is shown in Figure 29.

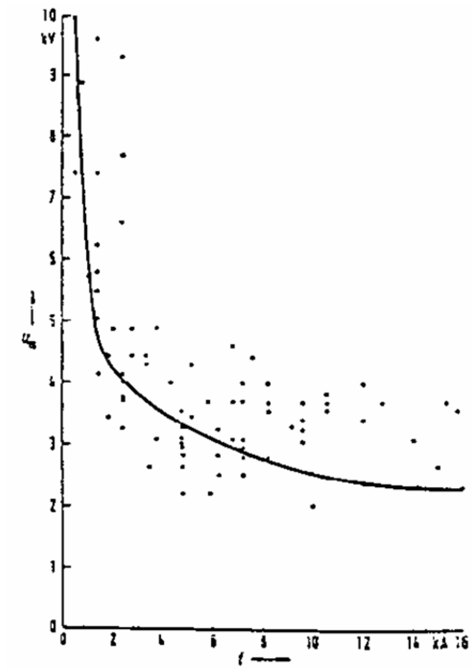


Figure 29 - Arc voltage-current characteristic for a SF_6 puffer type interrupter

Two references describing actual parallel switching tests between different circuit-breaker types are available and the above discussions can be tested against these tests [1, 2]. This is done in Table 13.

Table 13 - Analysis of actual parallel switching tests

Test Case	Predicted Outcome	Actual Outcome
CB1: SF_6 puffer CB2: SF_6 puffer I_1: 5 kA I_2: 35 kA Simultaneous contact parting just prior to current zero	Transfer from CB1 to CB2 due to negative characteristic of the arc voltage in CB1	Transfer from CB1 to CB2
CB1: SF_6 puffer CB2: SF_6 puffer I_1: 5 kA I_2: 35 kA Contact parting in CB2 3 ms prior to that in CB1 both well prior to current zero	Transfer from CB1 to CB2 around current zero crossing	Transfer from CB1 to CB2
CB1: SF_6 puffer CB2: SF_6 puffer I_1: 5 kA I_2: 35 kA Contact parting in CB2 at current zero 7 ms prior to contact parting in CB1	Transfer CB2 to CB1 on the basis of the staggered contact parting times	Transfer from CB2 to CB1
CB1: SF_6 puffer CB2: Minimum oil I_1: 4,6 kA I_2: 27,2 kA Simultaneous contact parting at current zero	Transfer from CB1 to CB2 based on low current and associated arc voltage in general or transfer from CB2 to CB1 if arc voltage builds up faster in CB2	Transfer from CB2 to CB1
CB1: SF_6 puffer CB2: Minimum oil I_1: 4,6 kA I_2: 27,2 kA Simultaneous contact parting in both CB1 and CB2 in quarter cycle prior to current zero	Transfer from CB1 to CB2 based on low current and associated arc voltage given that the period of significant change of arc voltage is not involved	Transfer from CB1 to CB2

Based on the limited information in the reference, the outcomes appear reasonably predictable, although it may be argued that some cases fall into grey areas. However, it can be stated with certainty that, if the characteristics of the arc voltages of both circuit-breakers is known, then the outcome can be definitively predicted.

11.5 Conclusions

The perceived risk with parallel switching is that current transfer will occur after an arcing time greater than one loop and thus approach an evolving fault type situation. To avoid this, it is often suggested that one or other of the two circuit-breakers be staggered by a time equal to one loop of current. However, introducing a time delay into a protective trip operation is unlikely to find favour with any utility and, on a balance of probabilities basis, appears to be unnecessary. The reasons for this are discussed below bearing in mind that sometimes the unpredicted can indeed happen if only on a very low probability basis.

As noted earlier, experience indicates that parallel switching is not a real issue requiring resolution but rather one of understanding the duty. The analysis above supports the notion that the arc voltages alone may be the driver that ensures the transfer of current from one circuit-breaker to the other within a time period of one loop. There is, however, an inherent staggering of the opening times between the different circuit-breaker types and the question is how this influences the interaction between the two circuit-breakers. On the basis that the current will tend to transfer from the circuit-breaker which opens first, Table 12 can be revised as shown below in Table 14.

Table 14 - Current transfer directions for parallel circuit breakers with inherent opening times and arc voltages

CB1	Current transfer direction based on: Arc voltage	Opening time	CB2
Oil	→ ←	– *	Oil
Oil	←	←	Air-blast
Oil	→	←	SF_6
Oil	→	→ ** ←	Vacuum
Air-blast	→ ←	– *	Air-blast
Air-blast	→	→	SF_6
Air-blast	→	→	Vacuum
SF_6	→ ←	– *	SF_6
SF_6	→	→ ** ←	Vacuum
Vacuum	→ ←	– *	Vacuum

* For like circuit-breakers with the same opening time, the current will transfer from the circuit-breaker with the highest arc voltage.

** Applies at medium voltage only and dependent on which circuit-breaker opens first.

At high voltages, only in the case of an oil and an SF_6 circuit-breaker is there an apparent conflict between the hierarchy of the arc voltages and the opening time. Dependent on the difference between the contact parting times it follows that:

- if the contact parting time spread between the two circuit-breakers is at least a quarter-cycle, then the current in the SF_6 circuit-breaker will probably transfer totally to the oil circuit-breaker before it opens.
- if the contact parting time spread is less than a quarter-cycle, then either the above scenario will occur or the current will start to transfer to the oil circuit-breaker and then reverse direction due to the arc voltage in the oil circuit-breaker.

At medium voltages, the same reasoning applies for oil and SF_6 circuit-breakers as discussed above. Where an oil or SF_6 circuit breaker is paralleled with a vacuum circuit-breaker, the following is likely to occur:

- if the vacuum circuit-breaker opens first, the current will transfer to the still closed oil or SF_6 circuit-breaker if a current zero crossing occurs before the latter circuit-breakers open; if no current zero crossing occurs, then the current in the latter circuit breakers will transfer to the vacuum circuit-breaker on opening.
- if the vacuum circuit-breaker opens last, the total current will be transferred to it.

Finally, what is the influence of frequency? The answer to this is that 60 Hz is more favourable to successful parallel switching than 50 Hz. The reason for this is the more frequent occurrences of current zero crossings and their associated significant changes in arc voltage which are conducive to current transfer in one direction or the other.

11.6 References

[1] S.S. Berneryd, "Improvement Possible in Testing Standards for High-Voltage Circuit Breaker. Harmonization of ANSI and IEC Testing." (See Discussion.) IEEE Transactions on Power Delivery, Vol. 3, No. 4, October 1988.

[2] S.S. Berneryd, "Parallel switching with SF_6 puffer circuit breakers." IWD 13-00 (WG11) 06.

12 Application of current limiting reactors

12.1 Introduction

Current limiting reactors applied to limit fault currents are usually installed at the substation distribution level [1]. Large capacity step-down substations are commonly used to supply distribution systems and the short circuit levels on the low voltage buses and feeders can be very high. The reactors can be installed on the buses or the feeders, or even in the transformer neutrals. The preferred location for overhead distribution systems is on each feeder.

The advantages offered by the use of series reactors on feeders are:

- circuit breakers, disconnectors and associated buswork can be rated for a lower short circuit level;
- the short circuit level imposed on downstream devices and customer installations is lower; also the possible risk for burndown of aerial conductors is virtually eliminated;
- the transformers are exposed only to the lower level faults which is significant given that the distribution feeder fault is the most common fault on power systems;
- joint use of poles for power distribution and communications purposes are facilitated.

Important considerations when using series reactors include equipment cost, space requirements and the installation cost, watt and var losses and regulation through the reactor. The reduction in the fault level is of the order of three or more: in one typical case in North America, where 5 mH reactors are applied in feeders, the fault level is limited to maximum 6 kA as opposed to in excess of 20 kA without the reactors. Overall reactor values in the range 2 to 5 mH are used.

Fewer bus reactors could be applied but such reactors are not attractive from a regulation perspective and watts loss. Transformer neutral reactors are also unattractive being effective only for single-line to earth faults.

Current limiting reactors are also used in shunt capacitor bank installations. The purpose of the reactors is to limit the inrush current through the bank circuit-breaker on energisation to 20 kA peak at 4250 Hz. This applies to single bank energisation or back-to-back bank energisation. Reactor values in this application are in the range 5 mH to 50 mH.

Only dry-type reactors are used in these applications today. The reactor electrical characteristics are thus a low inductance value and low stray capacitance values in the order of a few hundred Pico farad. The TRVs associated with the reactors on clearing feeder faults or faults between the reactor and the capacitor bank are fast rising with significant amplitudes. For the feeder case, circuit-breaker failures have been attributed to the reactor TRV [2].

12.2 Feeder case TRVs

Figure 30 shows the measured TRV for a three-phase ungrounded fault on a 25 kV feeder with a current limiting reactor. This TRV shape is typical and shows a fast transient oscillation due to the reactor superimposed on the slower transient oscillation determined by the source impedance and the local capacitances [3].

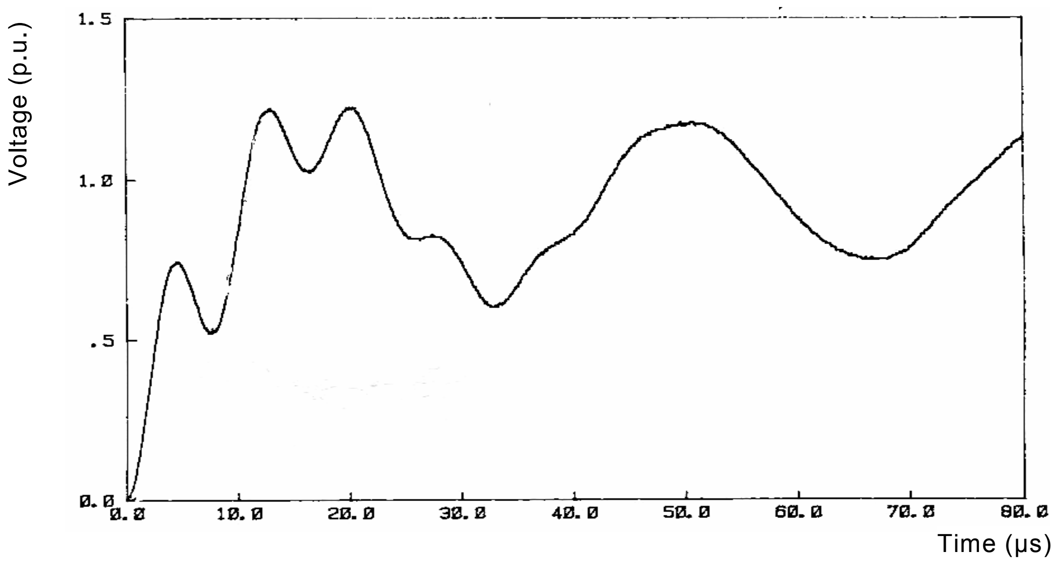
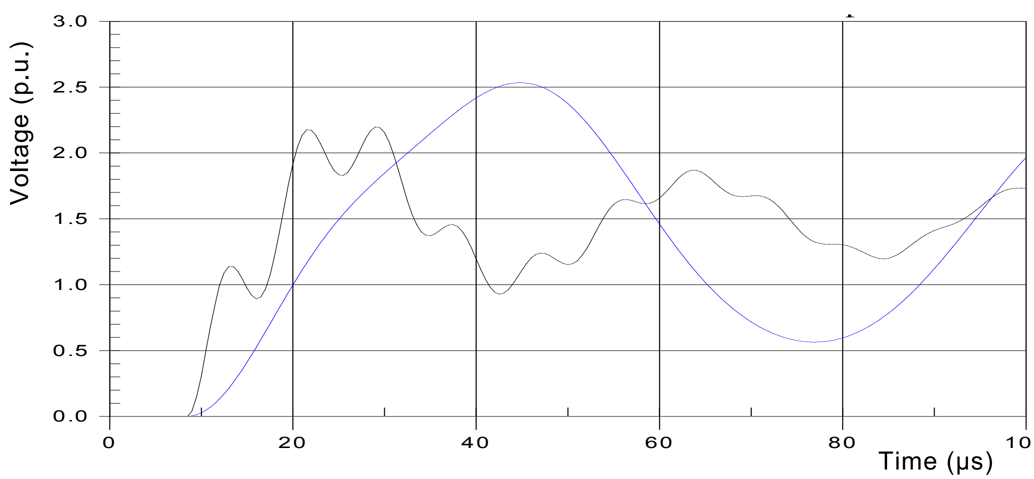


Figure 30 - TRV for three-phase ungrounded fault on 25 kV feeder with current limiting reactor (1 p.u. = 30,6 kV peak)

The fast transient oscillation can be dealt with by adding a capacitor across the reactor. This approach has advantages over applying the capacitor to earth in that it can actually be installed inside the reactor assembly [2]. Figure 31 shows an EMTP simulation for the case shown in Figure 30 without and with 20 nF applied across the reactor. During normal service the capacitor is exposed to the minimal voltage drop across the reactor and only experiences high voltages on fault occurrence.



Solid line: TRV without capacitance

Dashed line: TRV with capacitance

Figure 31 - EMTP simulation for case in Figure 30 with and without parallel capacitance (1 p.u. = 20,4 kVpeak)

12.3 Shunt capacitor case TRVs

This case can be illustrated by considering an EMTP study for a 66 kV, 50 MVAR ungrounded shunt capacitor bank with a 10 mH current limiting reactor. The TRV for a three-phase ungrounded fault between the reactor and the bank is shown in Figure 32. The effect of the reactor is very evident as is further shown in Figure 33.

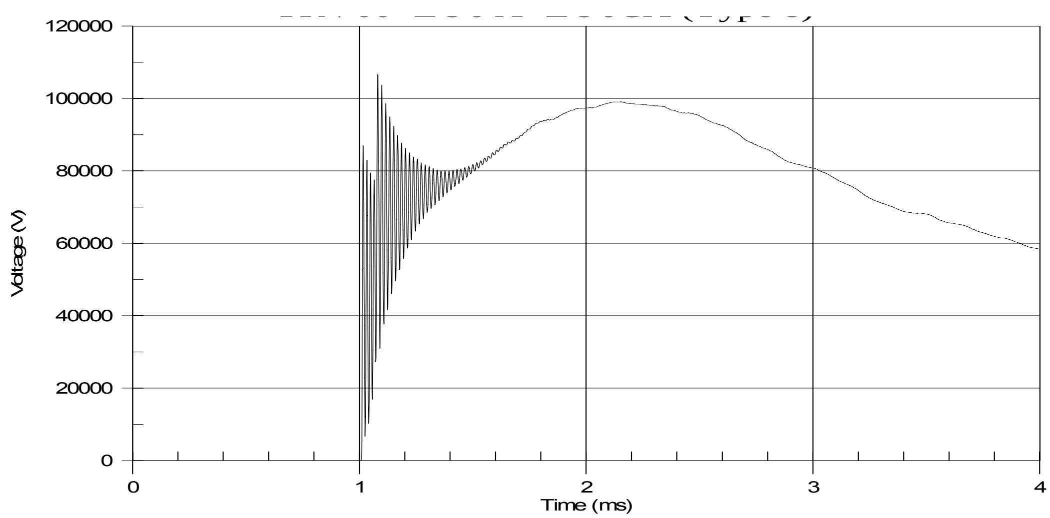


Figure 32 - TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor

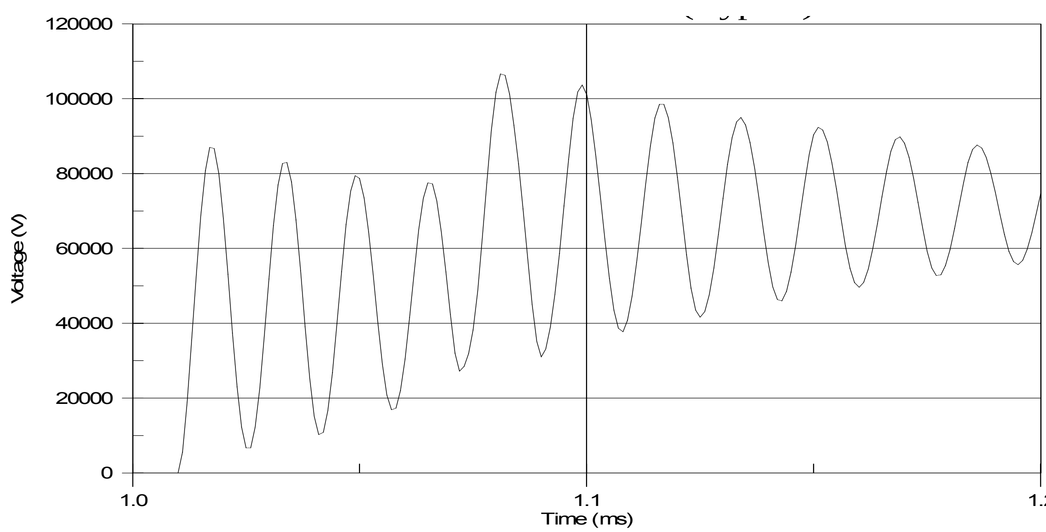


Figure 33 - Initial part of TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor

The effect of adding a 20 nF capacitor across the reactor is shown in Figure 34. The trace shows that the frequency of the reactor oscillation is reduced by about a factor of five.

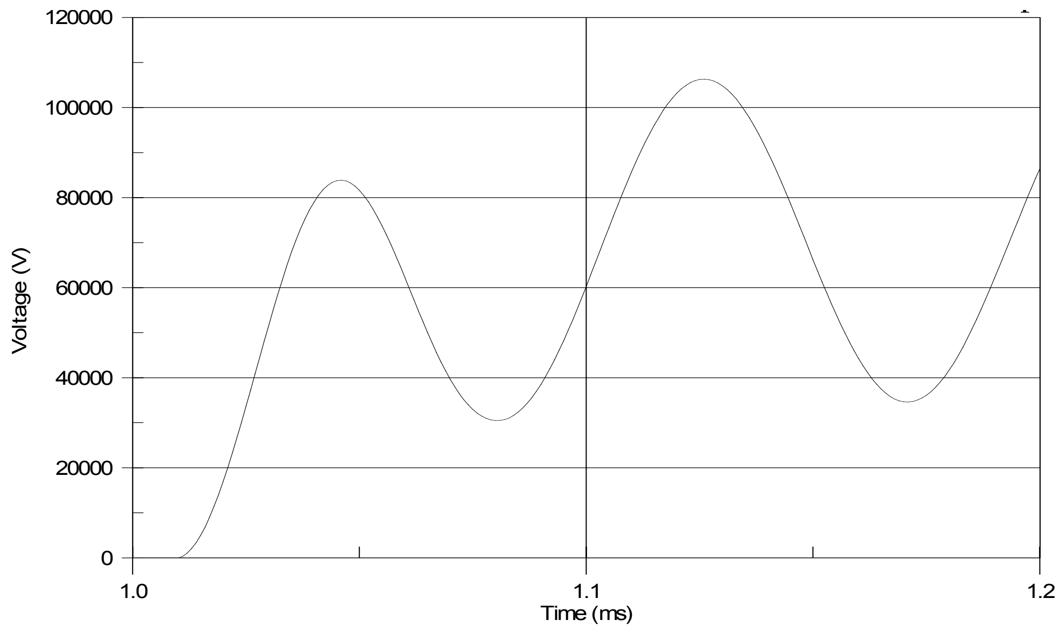


Figure 34 - Initial part of TRV for three-phase ungrounded fault on 66 kV shunt capacitor bank with 10 mH current limiting reactor with parallel 20 nF capacitor

12.4 Conclusion

Circuits which incorporate current limiting reactors exhibit unique TRVs on fault clearing. These TRVs are generally beyond the scope of those stated in circuit-breaker standards. Due diligence must therefore be exercised in applying circuit-breakers in such circuits.

12.5 References

[1] K.K. Nishikawara, "Application of Current Limiting Reactors in Substations." Canadian Electrical Association Spring Meeting, March 1980, Montreal, Canada.

[2] D.F. Peelo, G.S. Polovick, J.H. Sawada, P. Diamanti, R. Presta, A. Sarshar and R. Beauchemin, "Mitigation of Circuit Breaker Transient Recovery Voltages Associated with Current Limiting Reactors." IEEE Transactions on Power Delivery, Vol. 11, No. 2, April 1996.

[3] CIGRE Technical Brochure 134 "Transient Recovery Voltages in Medium Voltage Networks." December 1998.

13 Non-sustained disruptive discharge (NSDD)

The IEC 62271-1 and IEC 62271-100 subclauses relevant to this chapter are:

3.1.126 Non-sustained disruptive discharge (NSDD)

3.7.4 Non-sustained disruptive discharge (NSDD)

6.111.11 Criteria to pass the test

NSDDs (Non-Sustained Disruptive Discharges) have been discussed, up to now, in a rather controversial manner. This phenomenon, which has been observed predominantly on vacuum circuit-breakers, may occur during capacitive current and short-circuit breaking current tests, but also at lower currents and voltages. NSDDs have not been identified in actual service.

An NSDD is defined as follows:

non-sustained disruptive discharge (NSDD)
disruptive discharge associated with current interruption, which does not result in the resumption of power frequency current or, in the case of capacitive current interruption does not result in current in the main load circuit

NOTE Oscillations following NSDDs are associated with the parasitic capacitance and inductance local to or of the circuit-breaker itself. NSDDs may also involve the stray capacitance to earth of nearby equipment.

An NSDD exhibits itself as a partial voltage change. Such changes can sometimes be clearly seen with normal time resolution measurements. This is particularly true in three-phase tests when the same polarity and magnitude of voltage change is observed in all three phases as the result of a shift in the voltage of the parasitic neutral capacitance to earth of a non-solidly earthed load produced by an NSDD. An example of this is seen in Figure 35. However, in other cases, a clear identification of an NSDD may require a high time resolution measurement to observe the high frequency current or voltage pulse of an NSDD as seen in Figure 36.

Further examples of NSDDs are given in Figure 37, Figure 38 and Figure 39.

The occurrence of NSDDs does not affect the performance of the switching device. Therefore, their number is of no significance to interpreting the performance of the device under test and need not be remarked upon in the test report.

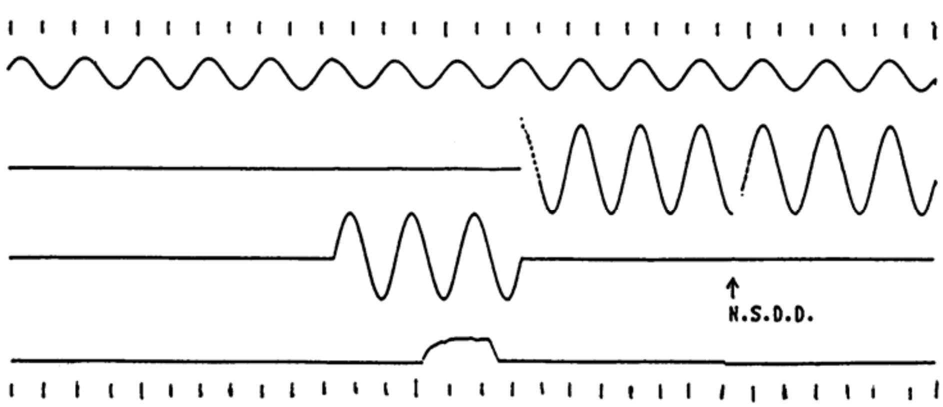


Figure 35 - An NSDD in a single-phase test circuit

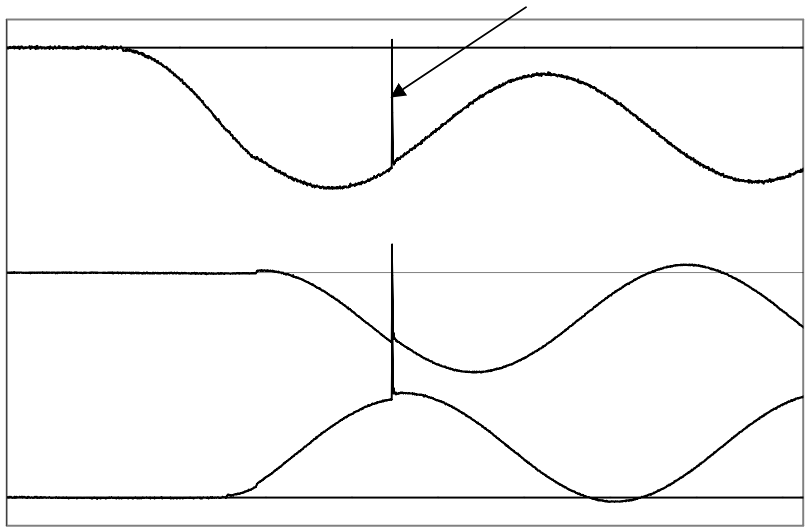


Figure 36 – An NSDD (indicated by the arrow) in a three-phase test

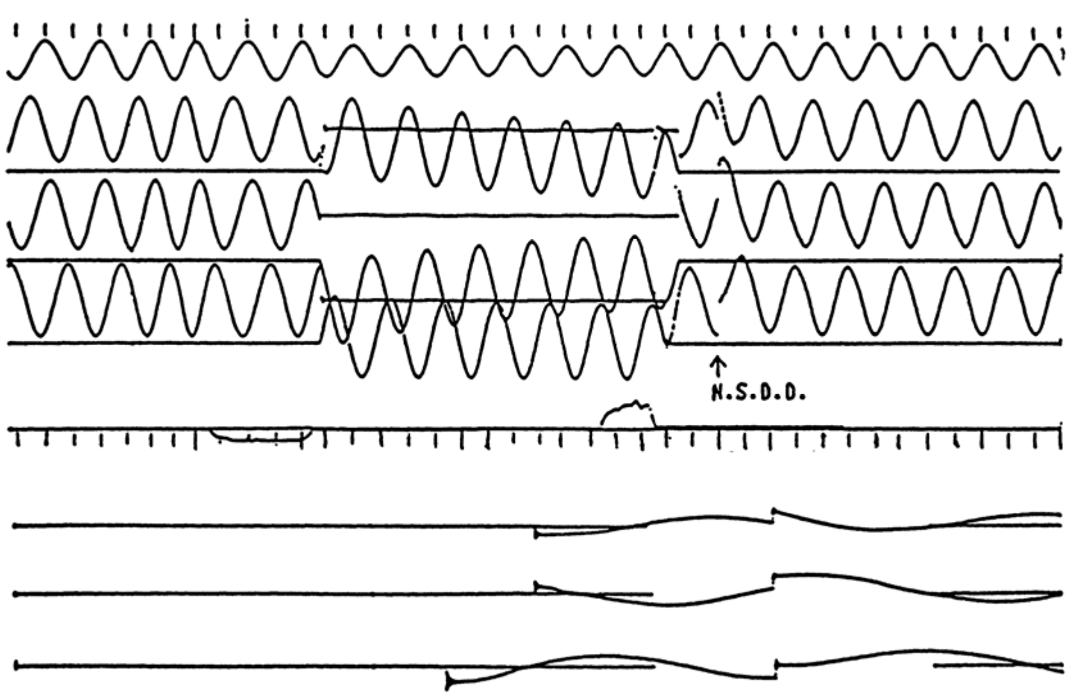


Figure 37 – A first example of a three-phase test with an NSDD causing a voltage shift in all three phases of the same polarity and magnitude

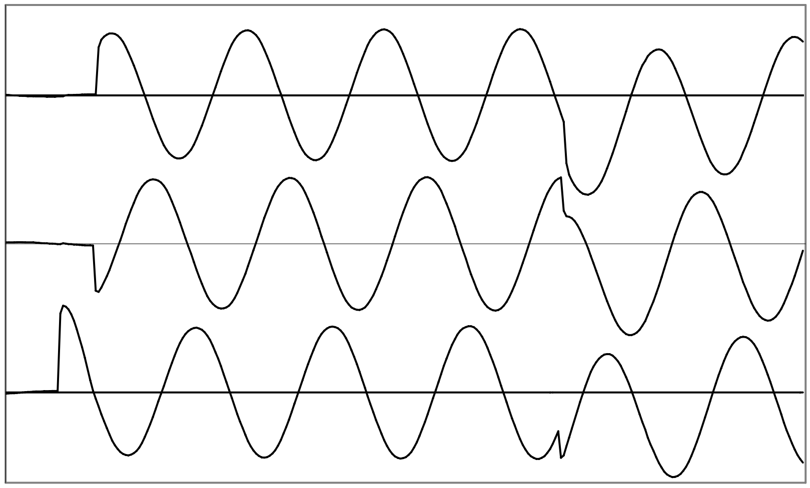
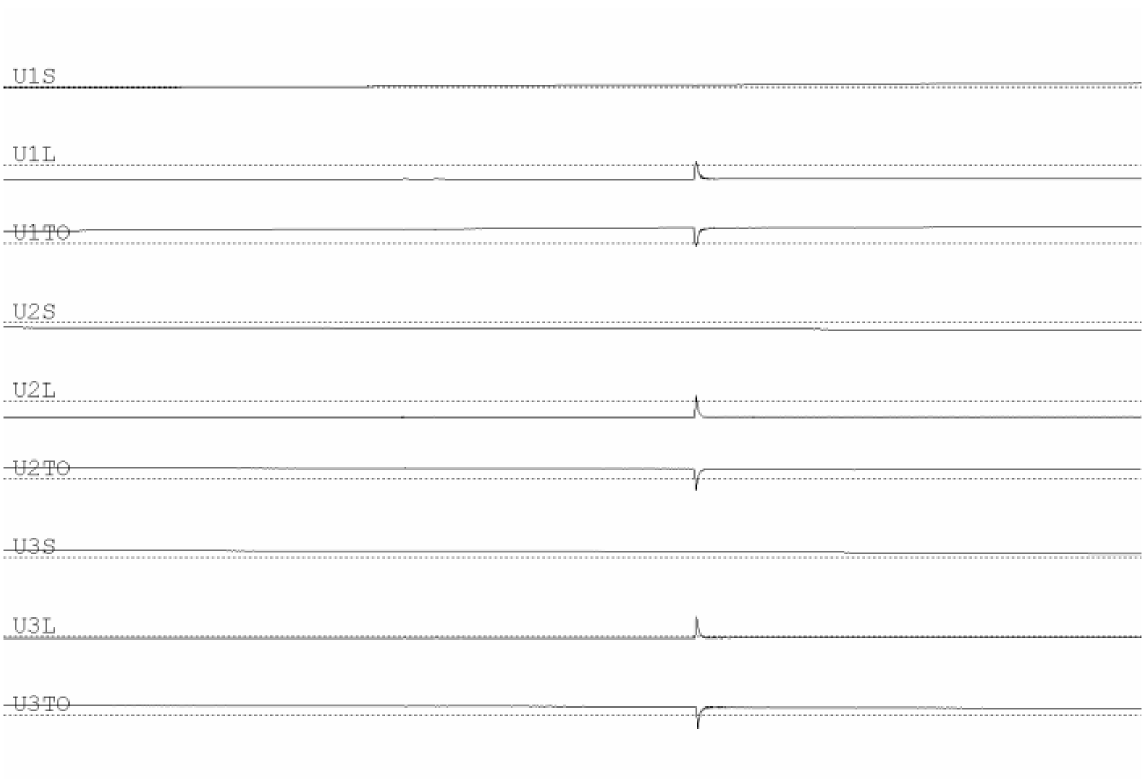


Figure 38 – A second example of three-phase test with an NSDD (indicated by the arrow) causing a voltage shift in all three phases of the same polarity and magnitude



Key

U1S, U2S, U3S	Source side voltages of the first, second and third phase
U1L, U2L, U3L	Load side voltages of the first, second and third phase
U1TO, U2TO, U3TO	Voltage across the first, second and third pole of the circuit-breaker

Figure 39 – A typical oscillogram of an NSDD where a high resolution measurement was used to observe the voltage pulses produced by the NSDD