Fault Current Limiters
Report on the Activities of CIGRE WG A3.10

by CIGRE Working Group 13.10 (*)

Abstract

A CIGRE Working Group (WG 13.10) was established in 1996 with the task to prepare a specification for fault current limiters. As a result of this work a report entitled "Functional Specification for a Fault Current Limiter" was published in 2001 [1]. The Working Group then continued its investigations on fault current limiters with a special focus on the topics "System Demands" [2], "State of the Art" [3] and "Testing" [4]. The original scope was the application of fault current limiters in distribution networks (1 kV < $U_r \leq 36$ (40.5) kV) and sub-transmission networks (52 kV $\leq U_r \leq$ 145 kV). Contributions related to fault current limiter applications in transmission networks (with U_r up to 420 kV) have however also been taken into account.

The members also undertook to assemble a bibliography on proposed solutions for the current limiting problem [1]. This showed that there has been considerable interest in the subject for almost forty years but with a few exceptions, there has been relatively little progress in developing suitable devices and bringing them to the market.

The present report gives an introduction to the problem of fault current limitation and an overview of the work carried out by the Working Group on this subject.

Keywords: Power System - Short-Circuit Current - Current Limiter

1. Fault Current Limitation

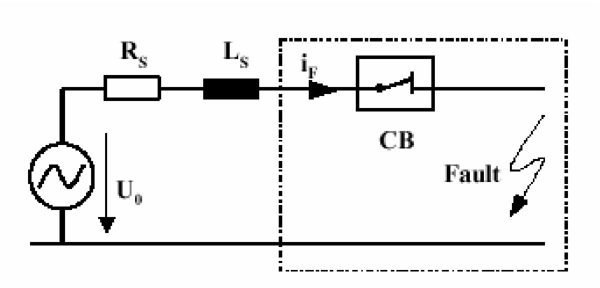
Faults in electrical power systems are inevitable. Apart from the damages in the vicinity of the fault - e.g. due to the effects of an electric arc - the fault currents flowing from the sources to the location of the fault lead to high dynamical and thermal stresses being imposed on equipment like overhead lines, cables, transformers and switchgear. The circuit-breakers further have to be capable of (selectively) interrupting the currents associated with such faults.

A growth in the generation of electrical energy and an increased interconnection of the networks lead to higher fault currents. Especially, the continuous growth in the generation of electrical energy has the consequence that networks approach or even exceed their limits with respect to the short-circuit current withstand capability. Therefore there is a considerable interest in devices which are capable of limiting fault currents. A fault current limiter can limit a fault current passing trough it within the first half cycle. The use of fault current

(*) Members:
H. Schmitt, Convenor (Germany), J. Amon (Brazil), D. Braun (Switzerland), F. X. Camescasse (France), M. Collet (France), G. C. Damstra (The Netherlands), H. Fukagawa (Japan), F. Gil Garcia (France), K.-H. Hartung (Germany), J. Kida (Japan), M. Saravolac (France)

limiters allows equipment to remain in service even if the prospective fault current exceeds its rated peak and short-time withstand current and in case of circuit-breakers also its rated short-circuit making and breaking current. Replacement of equipment can be avoided or at least shifted to a later date. In case of newly planned networks fault current limiters allow the use of equipment with lower ratings which renders possible considerable cost savings.

Figure 1a) shows a simple equivalent circuit for discussing the problems associated with fault current limitation in power systems [5]. Independent of the load current flowing prior to the fault, the short-circuit current starts with a certain rate-of-rise depending on the parameters of the circuit (source voltage U_0 and source impedance Z_S) and on the angle of initiation of the fault. When no limiting action takes place a fault current of shape i_1 in Figure 1b) will flow (prospective short-circuit current). This current will be interrupted by a conventional circuit-breaker at t_3.



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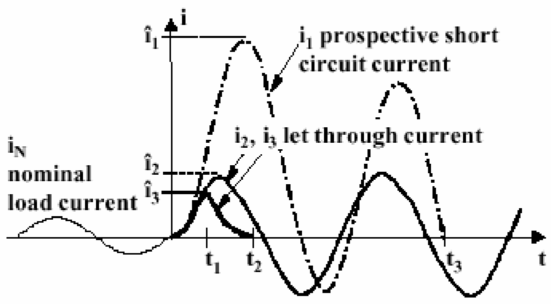

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Figure 1: Fault current limitation
a) Equivalent circuit representing a fault condition
b) Typical current waveforms due to a fault

The simplest way to limit the short-circuit current would be the use of a source impedance Z_S of an appropriate high value. The drawback of this solution is that it obviously also influences the system during normal operation, i.e. it results in considerable voltage drops at high load currents.

In order to be able to limit the first peak $\hat{I}_1$ of the short-circuit current i_1 it is necessary for the fault current limiting device to operate within the time interval t_1 and to cause a zero or negative rate-of-rise of the current. This can be achieved by inserting a voltage or an impedance of a high enough value into the circuit. Such an action requires the use of non-linear elements and leads to currents of the shape i_2 or i_3, respectively, depending on whether the current is only limited (i_2) or limited and also interrupted (i_3). Associated with this current limitation is the generation of an overvoltage which is proportional to the superimposed di/dt.

2. Description of the Limiting Behaviour of Fault Current Limiters

In the following characteristics and relations describing the limiting behaviour of fault current limiters are defined. These characteristics and relations cover the behaviour of existing fault current limiting devices (e.g. fault current limiting reactors, high-voltage current limiting fuses, I_S-limiters) as well as fault current limiting devices which are still under development (e.g. superconducting fault current limiters, solid-state fault current limiters). The following definitions apply:

Normal operation (for denominations see Figure 2):
- Peak value of rated current (I_r) - 1

Limitation (for denominations see Figure 2):
- Minimum initiating current ($\hat{I}_{min}$) - 2
- Maximum limited current ($\hat{I}_{max}$) - 3
- Peak short-circuit current ($\hat{I}_p$) - 4
- Peak value of follow current ($\hat{I}_{fol}$) - 5

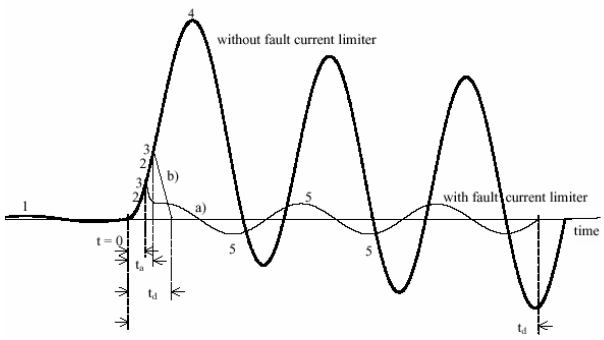


Figure 2: Definitions related to fault current limiters (see text)
a) Fault current limiting device with current limitation only
b) Fault current limiting device with current limitation and interruption

The performance characteristics of a fault current limiter can then be described using the relations given below:

η_0: follow current ratio (ratio of peak value of the follow current (5) to the peak value of the rated current (1)), also referred to as stationary current limiting ratio η_s

η_1: peak current limiting ratio (ratio of maximum limited current (3) to the peak short-circuit current (4))

η_2: current limiting ratio (ratio of peak value of the follow current (5) to the peak short-circuit current (4))

t_a: action time (time required from fault initiation at t = 0 to maximum limited current (3))

t_d: fault duration (time defined from fault initiation at t = 0 to fault current interruption)

t_r: recovery time (time between current interruption and return of the fault current limiter to its initial operation state at low impedance)

In addition to the above the following relations are also useful for describing the performance characteristics of a fault current limiter [6]:

η_d: dynamic current limiting ratio (ratio of maximum limited current (3) to the peak value of the rated current (1))

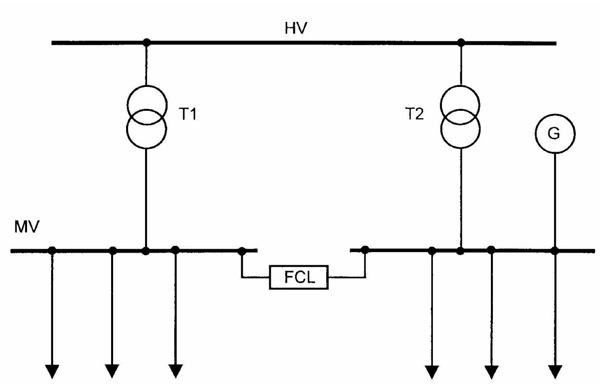
η_l: limiting ratio (ratio of maximum limited current (3) to the peak value of the follow current (5))

η_i: initiating ratio (ratio of minimum initiating current (2) to the peak value of the rated current (1))

3. Application of Fault Current Limiters

3.1 Installation of Fault Current Limiters

Fault current limiters can in principle be installed in bus ties/couplings (Figure 3), in incoming feeders (Figure 4) or in outgoing feeders (Figure 5).



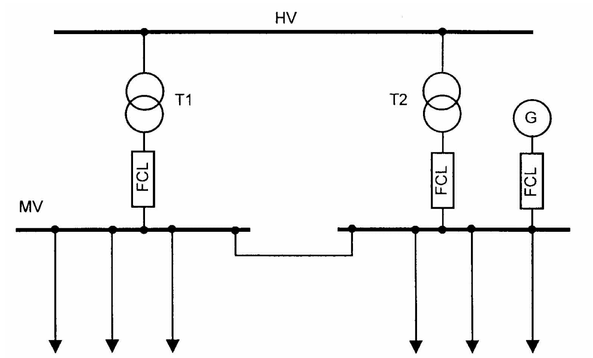
Note: circuit-breakers, disconnectors, etc. are not shown

Figure 3: Installation of a fault current limiter in a bus tie/coupling (example)

A fault current limiter in a bus tie/coupling limits the contribution of a sub-system to the total short-circuit current of the system.

The advantages of the use of a fault current limiter in a bus tie/coupling (refer to Figure 3) are:

- Reduction of the short-circuit current of the system (compared to the short-circuit current with closed tie circuit-breaker)
- Reduction of voltage sags and flicker due to the lower total source impedance
- Reduction of harmonics due to the lower total source impedance
- Higher system availability due to the parallel connection of the feeding generators and transformers
- Higher loads possible in a sub-system (higher than the ratings of the feeding generators and transformers in that sub-system)
- Even loading of the of feeding transformers due to their parallel connection



Note: circuit-breakers, disconnectors, etc. are not shown

Figure 4: Installation of fault current limiters in incoming feeders (example)

A fault current limiter in an incoming feeder limits on the one side the contribution of this feeder to the total short-circuit current of the system and on the other side the contribution of the remaining system to the short-circuit current in that particular feeder.

The advantages of the use of a fault current limiter in an incoming feeder (refer to Figure 4) are:

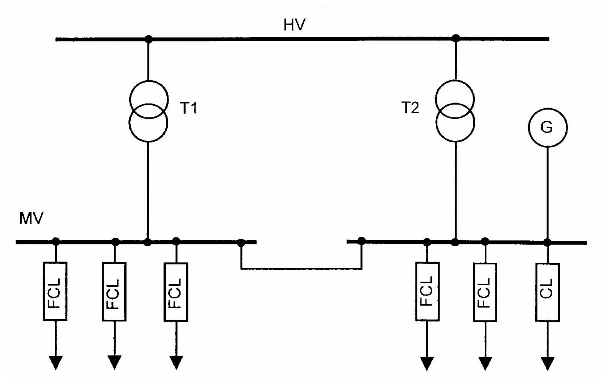
- Reduction of the short-circuit current of the system
- Reduction of voltage sags and flicker due to the lower total source impedance
- Reduction of harmonics due to the lower total source impedance
- Higher system availability due to the parallel connection of the feeding generators and transformers
- Even loading of the of feeding transformers due to their parallel connection

A fault current limiter in an outgoing feeder limits contribution of the system to the short-circuit current in that particular feeder.

The advantages of the use of a fault current limiter in an outgoing feeder (refer to Figure 5) are:

- Reduction of the short-circuit current in the particular feeder
- Reduction of voltage sags and flicker due to the lower total source impedance
- Reduction of harmonics due to the lower total

source impedance



Note: circuit-breakers, disconnectors, etc. are not shown

Figure 5: Installation of fault current limiters in outgoing feeders (example)

The results of an inquiry carried out by the Working Group regarding the preferred locations for installing fault current limiters are shown in Figure 6. From this survey follows that the majority of fault current limiters will be installed in bus ties (52 %) and incoming feeders (33 %).

3.2 System-Device Interactions

When a fault current limiter is installed in a system there will be interactions between the fault current limiter and the system. A list of some of the items which have to be taken into consideration when applying fault current limiters is presented.

3.2.1 Effects of a Fault Current Limiter on the System

3.2.1.1 Effects on Protection Schemes

- Relay settings
- Selectivity
- Protection blinding (especially in the case of directional protection)
- Compatibility with downstream fuses

3.2.1.2 Effects on Independent Power Producer Installations

- Generator stability
- Generator decoupling protection

3.2.1.3 Effects on Conventional Switchgear

- Transient recovery voltage of downstream circuit-breakers

3.2.1.4 Effects on System Reliability

- Reliability of the fault current limiter
- Effect of a no-trip of the fault current limiter when a trip is required
- Effect of a trip of the fault current limiter when no trip is required
- Failure mode of the fault current limiter in case of an internal fault
- Maintenance requirements of the fault current limiter

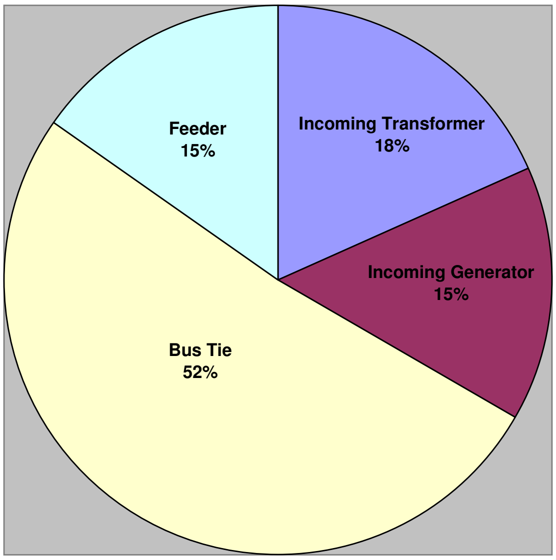


Figure 6: Preferred locations for installing fault current limiters

3.2.2 Effects of the System on a Fault Current Limiter

3.2.2.1 Undesirable Tripping of Fault Current Limiter

- Transient currents due to single-phase-to-earth faults in ungrounded cable networks
- Inrush currents due to transformer energisation
- Inrush currents due to capacitor bank switching
- Starting currents of motors

3.2.2.2 Ability of Fault Current Limiter to Withstand Short-Circuit Currents

In case of fault current limiters with current limitation only the fault current limiter has to be able to withstand the short-circuit current as long as required by the protection scheme applied (i.e. if applicable also during several reclosing cycles)

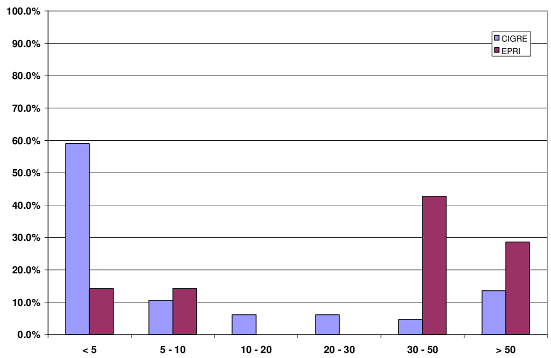
3.3 Requirements for Fault Current Limiters

The requirements imposed on a fault current limiter can be summarised as follows:
- Low impedance during normal operation (low voltage drop across the device)
- Low losses
- Adequate current limiting performance
- Compatibility with existing or planned protection schemes

- No deterioration of the limiting behaviour during the useful life
- High reliability
- Low maintenance requirements
- No risk for personnel
- Low impact on the environment

The Working Group specifically also investigated the requirements regarding the permissible number of limiting operations and the duty cycle. The results are indicated in Figure 7.

Apart from the above mentioned requirements the acquisition cost and operation and maintenance costs of course play an important role when a decision regarding the installation of a fault current limiter is made. The Working Group carried out an inquiry about the price customers are ready to pay for a fault current limiting device (Figure 8). For comparison purposes the results of two earlier surveys [7, 8] are also indicated.



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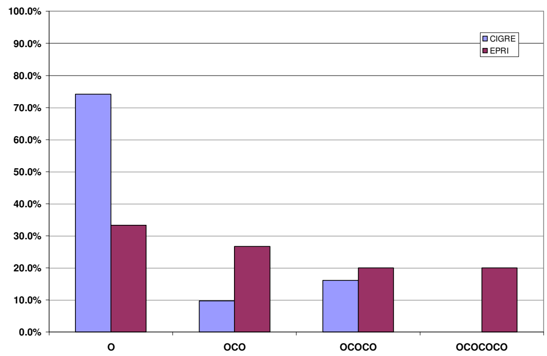

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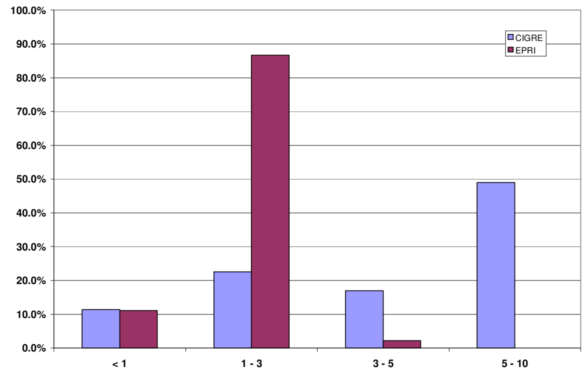
Figure 7: Requirements regarding the permissible number of operation and the duty cycle of a fault current limiter based on inquiries of CIGRE WG 13.10 and of EPRI [7]
a) Permissible number of operations
b) Duty cycle

3.4 Specifications for Fault Current Limiters

A specification for a fault current limiter must contain the following basic information:

- Rated voltage
- Rated insulation level
- Rated frequency
- Rated current and overload capability
- Rated current limiting performance (initiating current, limited current, follow current, action time, fault duration, recovery time, switching overvoltage)



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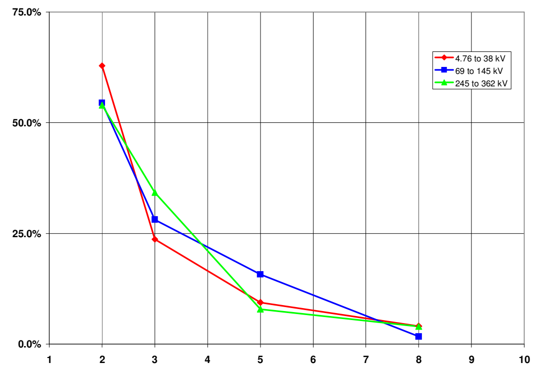

b)

Figure 8: Worth of a fault current limiter to a customer (price unit: price of a conventional circuit-breaker)
a) Inquiries of CIGRE WG 13.10 and of EPRI [7]
b) Inquiry of AEIC [8] (demand vs. price)

If the required current limiting performance is specified as ratio of the short-circuit current with fault current limiter operation to the short-circuit current without fault current limiter operation it should be clearly indicated whether this ratio refers to the short-circuit current at the fault location or the short-circuit current flowing trough the fault current limiter.

In case of fault current limiters which introduce a resistance into the circuit the fault current limiter not only limits the fault current but also shifts its phase which leads to an additional current limiting effect when a limited and an unlimited fault current sum up to a total short-circuit current

Also the following items need to be addressed in a specification:

- Installation (indoor or outdoor)
- Service conditions (normal or special)
- Requirements regarding dimensions and weight
- Three-phase or single-phase device
- Device with or without integrated series switches or disconnectors
- Requirements regarding the supervision (monitoring) of the device
- Etc.

4. State of the Art of Fault Current Limiters

Only fault current limiters for the application in medium-voltage networks (1 kV < $U_r \leq$ 36 (40.5) kV) and in high-voltage networks ($U_r \geq$ 52 kV) are considered. Fault current limiters for the applications in low-voltage networks (U_r < 1 kV) are not dealt with.

A comparison of the current limiting performance and other pertinent features (e.g. losses) of the different current limiting devices is outside the scope of this overview.

A distinction is made between passive and active fault current limiting measures (Figure 9) [5]. Passive measures make use of an already initially high source impedance both at normal and at fault conditions whereas active measures bring about a fast increase of the source impedance at fault conditions only.

Active fault current limiters can be further characterised as follows:

- self-triggered or external triggered
- with current limitation only or with current limitation and interruption
- resetable or non-resetable (parts of the fault current limiter need to be replaced after an operation)

It should be noted that instead of using fault current limiters the problems associated with increased fault current levels can also be coped with measures like:

- Uprating of existing switchgear and other equipment
- Changes in network topology, e.g. splitting of grids or splitting of busbars
- Introduction of higher voltage levels
- Use of complex control strategies like sequential tripping
- Etc.

These measures are not dealt with any further. Also not covered are measures like to use of FACTS-devices with fault current limitation (for instance a thyristor controlled series compensator with fault current limitation (e.g. Kayenta, U.S.A. [9])) or DC-links as such measures are hardly being installed for the purpose of limiting fault currents in the first place. Fault current limitation may nevertheless be an attractive by-product of such applications.

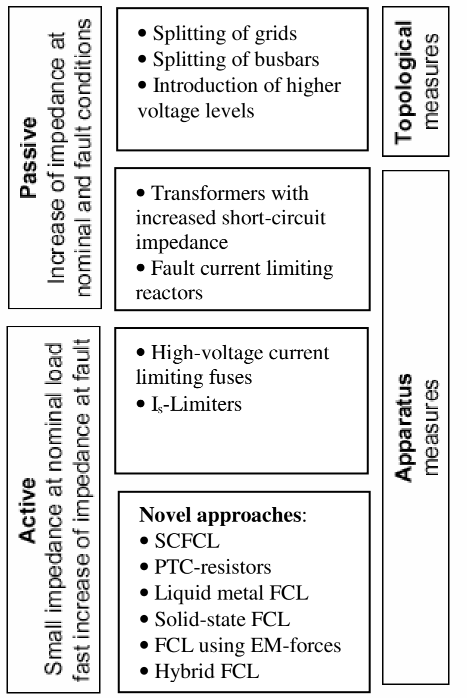

Figure 9: Overview of fault current limiting measures [5]

4.1 State of the Art

Table 1 gives an overview of fault current limiting devices which are (or have been) commercially available.

4.2 Novel Approaches

In Table 2 an overview of fault current limiting devices which are still in a research or development state is given. Prototypes of such devices may already have been installed in power systems. Only active measures are considered.

Many different types of fault current limiters have been proposed over the years. No pretension is made to give a complete coverage of all these devices.

Although many investigations have been carried out in the past and are currently being carried out the state of the art in the field of fault current limiting devices are conventional solutions like fault current limiting reactors, high-voltage current limiting fuses, pyrotechnic fault current limiters, etc. For the time being, none of the novel approaches led to an economically acceptable solution for a fault current limiter for medium-voltage or high-voltage networks.

5. Testing of Fault Current Limiters

Standards with rules for the testing are presently only

Table 1: State of the art

Type	Characteristics					Voltage Level	Lit.
	Passive/ Active	**Triggering Method**	**Current Interruption**	**Resetable**	**Hybrid**		
Fault current limiting reactor	Passive	-----	-----	-----	-----	MV, HV	
Transformer with increased short-circuit impedance	Passive	-----	-----	-----	-----	MV, HV	
High-voltage current limiting fuse	Active	Self-triggered	Yes	No	No	MV	[10]
Pyrotechnic fault current limiter (I_s-Limiter)	Active	External triggerd	Yes	No	Yes	MV	[11]
Resonance link ("Kalkner"-Kupplung)	Active	Self-tiggered	No	Yes	No	MV, HV	[12, 13]

Table 2: Novel approaches

Type	Characteristics					Voltage Level (Prototypes)	Lit.
	Passive/ Active	**Triggering Method**	**Current Interruption**	**Resetable**	**Hybrid**		
Superconducting fault current limiter: Resistive type	Active	Self-triggered	No	Yes	No	MV	[14, 15]
Superconducting fault current limiter: Shielded iron core type	Active	Self-triggered	No	Yes	No	MV	[16]
Superconducting fault current limiter: Saturated iron core type	Active	Self-triggered	No	Yes	No	MV	[17]
Superconducting fault current limiter: "Current controller" type	Active	External triggerd	1)	Yes	No	MV	[18]
Fault current limiter based on PTC-resistors 2)	Active	Self-triggered	Yes 3)	Yes 4)	No	MV	[19]
Liquid metal fault current limiters	Active	Self-triggered	No	Yes	No	-----	[20]
Current limiting solid-state switch	Active	External triggerd	Yes	Yes	No	MV	
Solid-state fault current limiter with current limiting impedance	Active	External triggerd	Yes	Yes	No	MV	
Solid-state fault current limiter based on hybrid principle	Active	External triggerd	Yes	Yes	Yes	MV	
Current limiter based on high arc-voltage	Active	External triggerd	Yes	Yes	1)	MV	[21, 22]
Resonance link with switching device (vacuum, solid-state)	Active	External triggerd	No	Yes	No	-----	

Notes:
1) depending on the layout of the device
2) PTC: positive temperature coefficient
3) with integrated series switch
4) numbers of operation is limited

available for fault current limiting reactors (IEC 60289 [23]) and for high-voltage current limiting fuses (IEC 60282-1 [24]). Rules for the testing of other types of fault current limiters need to be established in the future. In this section some basic considerations about the tests to be carried out are given. It is understood that for different types of fault current limiters different test procedures will apply.

5.1 Dielectric Tests

Dielectric tests as described in IEC 60694 [25] have to be performed with the fault current limiter in closed position between phase and ground and between the phases. The test voltages should be chosen in accordance with Tables 1 and 2 of IEC 60694.

If a fault current limiter (or the combination of a fault current limiter and a series switch) can have an open position the dielectric performance in this position has also to be verified, independent of the nature of the gap (e.g. solid-state switch, mechanical switch). The voltage imposed on an open circuit-breaker in a grid coupling could serve as a basis for determining the test voltages in this case. Additionally, the long term performance shall be investigated, especially in the case of semi-conductors.

5.2 Temperature-Rise Tests

Temperature-rise tests including the measurement of the resistance of the main current path have to be performed in accordance with IEC 60694 [25]. The test current shall be equal to the rated current of the fault current limiter. The temperature rise of the contacts and other parts should be within the limits specified in Table 3 of IEC 60694. The admissible temperature rise of non-accessible parts such as contacts in vacuum interrupters, silicon wafers in semiconductor devices or superconducting materials will have to be considered separately.

If a fault current limiting device has an overload capability this shall also be verified by tests.

5.3 Short-Time Withstand Current Tests

In case of self-triggered fault current limiters (e.g. superconducting fault current limiters) the prospective short-circuit current shall be applied to the device. The purpose of the test is to verify the current limiting performance (i.e. the initiating current, the limited current and the follow current).

External triggered fault current limiters can be divided in two sub-groups:

- Devices which are capable of withstanding the prospective short-circuit current of the system (e.g. pyrotechnic fault current limiters): These devices shall be subjected to a peak and short-time withstand current test with the prospective short-circuit current without any limiting operation. The operation of the triggering device shall be tested separately to verify the trigger levels required in accordance with the ratings of the system.
- Devices which are not capable of withstanding the prospective short-circuit current of the system (e.g. solid-state fault current limiters): These devices shall be subjected to a peak and short-time withstand current test with the prospective short-circuit current with the triggering device operative. This test will therefore at the same time serve to verify current limiting performance.

5.4 Short-Circuit Making and Breaking Tests

These tests apply to fault current limiting devices with current interruption. The short-circuit current breaking tests shall be carried out at the rated voltage of the fault current limiter. The source impedance of the test circuit shall be chosen so that the required prospective short-circuit current flows in the circuit. Tests at different fault initiation angles are to be performed in order to verify that the fault current limiter is capable of interrupting both symmetrical and asymmetrical currents. The transient recovery voltage of the test circuit shall be defined taking into account the network condition prevailing at the location where the fault current limiter will be installed.

When a fault current limiter can be used for closing a circuit, short-circuit current making tests need also to be carried out.

5.5 Endurance Tests

In case of fault current limiters suitable for more than one limiting operation an endurance test with an appropriate number of limiting operations shall be carried out.

5.6 Electromagnetic Compatibility (EMC) Tests

Electromagnetic compatibility tests shall be carried out in accordance IEC 60694 [25]. Depending on the type of fault current limiter and triggering device it may be advisable to supplement the tests described in IEC 60694 by additional EMC-tests.

6. Outlook

The management of power systems in countries in all parts of the world is changing nowadays and there is a strong tendency towards separating generation from transmission. In this deregulated environment the utilities responsible for operating the networks are losing control over the siting and scheduling of generation. The connection of independent power producers to transmission, sub-transmission and distribution networks causes an increase of short-circuit currents not included in previous long-term planning forecasts. A consequence of this development is that in certain part of the networks the short-circuit currents approach or even exceed the limiting values.

The problem of excessive short-circuit currents has therefore become an import issue for the operators of power systems and there are clear indications for a growing interest in devices which are capable of limiting fault currents.

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