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FAULT CURRENT LIMITERS IN ELECTRICAL MEDIUM AND HIGH VOLTAGE SYSTEMS

Working Group
A3.10
(High Voltage Equipment)

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Fault Current Limiters in
Electrical Medium and High Voltage Systems

Working Group 10
of
Study Committee A3 (High Voltage Equipment)

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Foreword

CIGRE Working Group A3.10 was established in 1996 to prepare a specification for a fault current limiter (FCL).
At the same time the members undertook to assemble a bibliography on current limiting publications and proposed solutions for the current limiting problem. This showed that there has been considerable interest in the subject for almost forty years but with a few notable exceptions, there has been relatively little progress in developing the hardware and bringing it to market.

In 2001 a first report together with an extensive reference list was put into the CIGRE web and an excerpt of 6 pages was published in Electra.
In the mean time WG A3.10 continued the work with focus to the items “System Demands”, “Testing” and “State of the Art”. The work results in 3 reports which were finished in 2002 and put into the CIGRE web too. The reports can be visited at the address http://www.e-cigre.org/ in the member area of the CIGRE web.

In 2002 Study Committee A3 decided to publish the complete work of Working Group A3.10 as Technical Brochure.
This brochure contains 4 major parts:

Part A:	Fault Current Limiters – State of the Art
Part B:	Functional Specification for a Fault Current Limiter
Part C:	Fault Current Limiters - System Demands
Part D:	Fault Current Limiters - Testing

An extensive reference list regarding limiting technology is included as Part E to this brochure as well.

During the years of joint work the members of the Working Group A3.10 included the following:

A. Greenwood	US	(Convenor until Aug. 2000)
H. Schmitt	DE	(Convenor since Sept. 2000)
J. Amon Filho	BR	
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Content

Part A

Fault Current Limiters – State of the Art

A Fault Current Limiters – State of the Art

1. Introduction

Faults in electrical power systems cannot be avoided. 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, transformer 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 reach 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. The use of fault current limiters allows equipment to remain in service even if the prospective fault current exceed 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.

The present report gives an overview of the state of the art of fault current limiting devices. The state of the art comprises fault current limiting devices which are (or have been) commercially available. Devices which are still in a research or development stage are covered in the section novel approaches. Many different types of fault current limiters have been proposed over the years. This report therefore does not pretend to give a complete coverage of all these devices.

Only fault current limiters for the application in medium-voltage networks (rated voltage: 1 kV ... 36 kV (40.5 kV)) and in high-voltage networks (rated voltage: > 36 kV (40.5 kV)) have been considered. Fault current limiters for the applications in low-voltage networks (rated voltage: < 1 kV) are not dealt with.

A distinction is made between passive and active fault current limiting measures (Figure A 1) [1]. Passive measures increase the source impedance both at nominal and at fault conditions whereas active measures bring about a fast increase of the source impedance at fault conditions only.

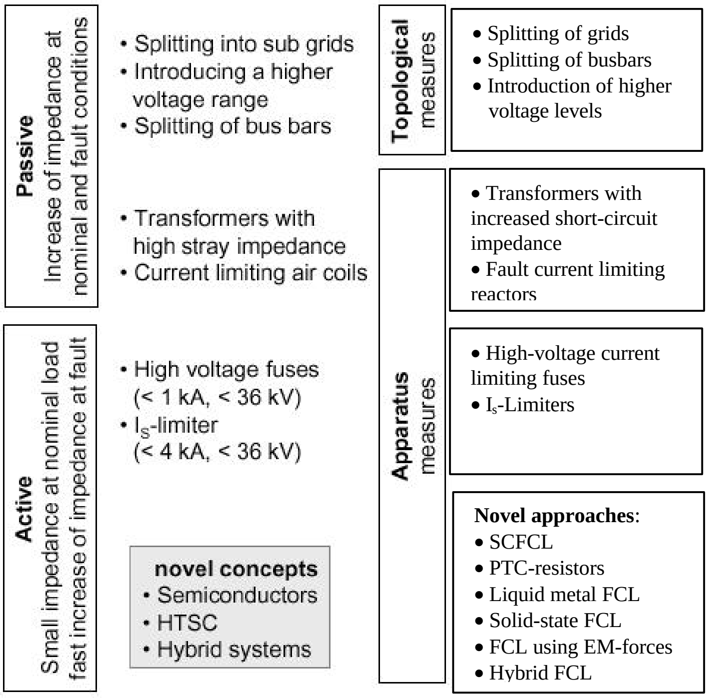

Figure A 1: Overview of fault current limiting measures

Active fault current limiters can be further characterised as follows:

- self-triggered or external triggered
- with or without current interruption
- able or not able to carry the short-circuit current for the duration of the short-circuit (i.e. for 1 s or 3 s, only applicable for devices without current interruption)
- resettable or non-resettable (parts of the fault current limiter need to be replaced after an operation)

Instead of using fault current limiters the problems associated with increased fault current levels can also be coped with measures like:

- Changes in network topology, e.g. splitting of grids or splitting of busbars
- Introduction of higher voltage levels
- Selection of transformers with a higher short-circuit impedance
- Uprating of existing switchgear and other equipment
- Use of synchronous circuit-breakers
- Use of complex control strategies like sequential tripping

These measures are not dealt with any further in the present report. Also not covered are measures like the use of HVDC converters as such measures are hardly being installed for the purpose of limiting fault currents in the first place. Single-phase-to-earth faults in non-effectively earthed networks are outside the scope of this report, too.

A transformer concept using an interphase power controller (IPC) to limit fault currents [18] submitted from members of the Brazilian A3 could not be enclosed to the report.

2. Fault Current Limitation

Figure A 2 shows a simple equivalent circuit for discussing the problems associated with fault current limitation in power systems [1]. 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 places a fault current of shape i_1 in Figure A 3 will flow (prospective short-circuit current). This current will be interrupted by a conventional circuit-breaker at t_3.

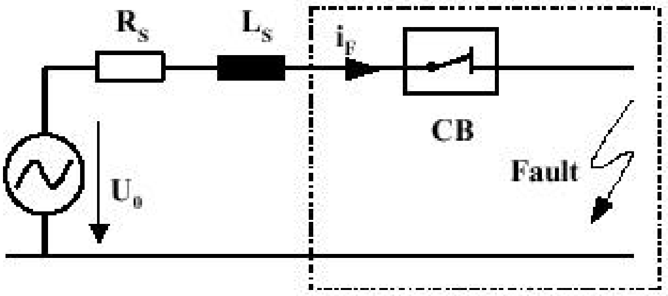

Figure A 2: Equivalent circuit representing a fault condition

The simplest way to limit the short-circuit current would be the use of a source impedance Z_S of an appropriate high value. Some solution used in medium-voltage and high-voltage networks are based on this method. The drawback is that it obviously also influences the system during normal operation.

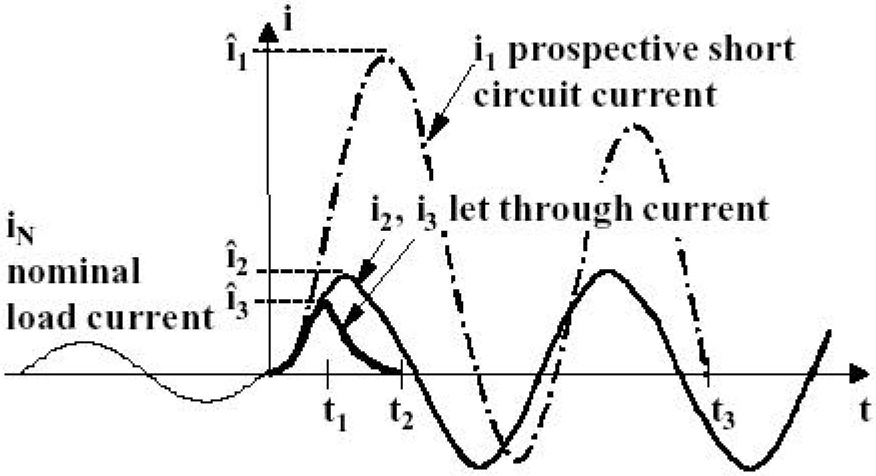

Figure A 3: Typical current waveforms due to a fault [1]

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 limiting device to operate within the time interval t_1 and to limit the rate of rise of the current to a value $di/dt \leq 0$. This can be achieved by inserting a voltage 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).

3. State of the Art

In this section an overview of fault current limiting devices which are (or have been) commercially available is given. Devices which are made up of commercially available components and which are put together with some engineering effort for special purpose applications are also covered in this section.

3.1 Medium-Voltage Networks (Rated Voltage: 1 kV ..... 36 kV (40.5 kV))

3.1.1 Passive Measures

3.1.1.1 Fault Current Limiting Reactors

Description

Fault current limiting reactors limit the fault current due to the voltage drop across their terminals. They are normally built as dry-insulated, air-cored and naturally cooled coils and are supplied as single-phase as well as three-phase units (Figure A 4). Since the reactance must remain constant during fault conditions only the air-cored construction is suitable for this application.

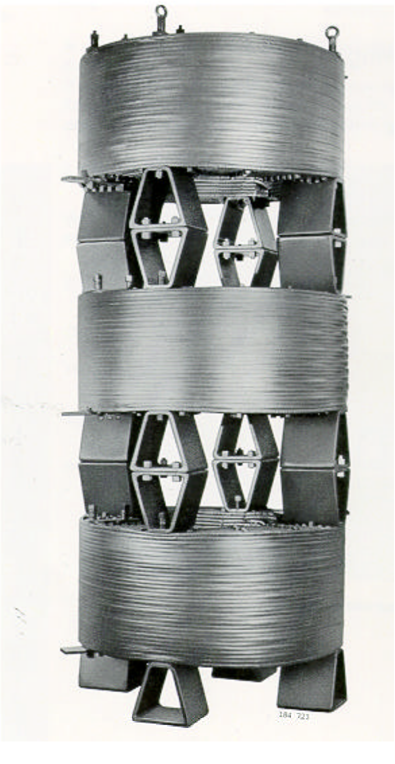

Figure A 4: Three-phase fault current limiting reactor
Inductance: 2 mH
Rated current 1250 A

Technical Data

Fault current limiting reactors are available for rated currents up to 2500 A at rated voltages up to 36 kV.

3.1.2 Active Measures

3.1.2.1 High-Voltage Current Limiting Fuses

Description

Fuses have been produced well for over 100 years and they are by far the lowest cost means of protecting against fault currents. A high-voltage current limiting fuse consists of conductor bands, normally of silver, which are arranged spirally in a sealed dry quartz sand filling in the interior of an extremely thermally resistant ceramic pipe (Figure A 5). The conductor bands are designed with a narrower cross-section at many points to ensure that in the event of an overcurrent or a fault current, a defined melting will occur at many points simultaneously. The resulting arc-voltage is high enough to limit a fault current to a value substantially less than the prospective peak value [2].

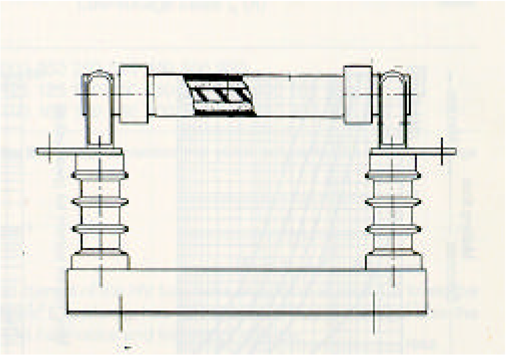

Figure A 5: High-voltage current limiting fuse (fuse base with fuse link)

Characteristics

- self-triggered
- with current interruption
- non-resettable

Technical Data

The typical range for rated currents of high-voltage current limiting fuses is up to 315 A at rated voltages up to 12 kV, for rated currents up to 160 A at rated voltages up to 24 kV and for rated currents up to 100 A at rated voltages up to 36 kV. Higher rated currents can be achieved by connecting fuses in parallel.

3.1.2.2 Pyrotechnic Fault Current Limiters (I_s-Limiter)

Description

The I_s-Limiter consists in principle of an extremely fast switch, able to carry a high rated current but having no fault current limiting capacity, and a high rupturing capacity fuse arranged in parallel (Figure A 6). In order to achieve the desired short opening time, a small charge is used as the energy store for opening of the switch (main conductor). When the main conductor is opened, the current continues to flow through the parallel fuse, where it is limited within 0.5 ms and then finally interrupted at the next voltage zero passage [3].

The current flowing through the I_s-Limiter is monitored by an electronic measuring and tripping device. At the very first rise of a fault current, this device decides whether tripping of the I_s-Limiter is necessary. In order to reach this decision, the instantaneous current and rate of current rise at the I_s-Limiter are constantly measured and evaluated. When the setpoints are simultaneously reached or exceeded, the I_s-Limiter trips in the faulty phases. After operation the limiter has to be disconnected by a series-connected circuit-breaker in order to get access for changing the tripped I_s-Limiter inserts.

Since the invention of the I_s-Limiter in 1955, several thousand devices have been successfully used in DC, AC and particularly in three phase systems.

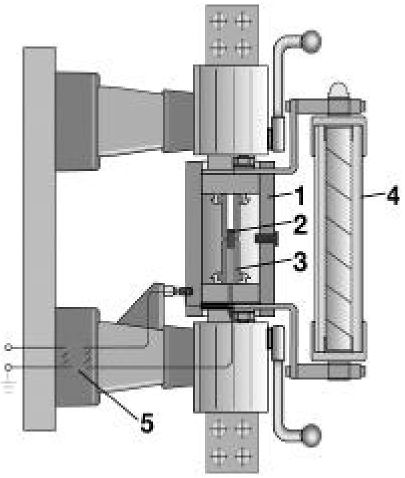

Figure A 6: Insert holder and insert of an I_s-Limiter
1 - Insulating tube
2 - Charge
3 - Bursting bridge (main conductor)
4 - Fuse
5 - Pulse transformer

Characteristics

• external triggered
• with current interruption
• non-resettable

Technical Data

I_s-Limiters are available for rated currents up to 4000 A at rated voltages up to 17.5 kV, for rated currents up to 3000 A at rated voltages up to 24 kV and for rated currents up to 2500 A at rated voltages up to 36 kV.

Ranges for I_s-limiters

Rated Voltage V	Rated Current A	Breaking Capability kA_{RMS} sym.
750	630 ... 5000	140
12000	630 ... 4000	210
17500	630 ... 4000	210
24000	630 ... 2500	140
36000	630 ... 2500	140

The example in Figure A7 demonstrates the fundamental function of the device: a short-circuit of 25 kA can flow through each transformer to the short circuit location behind the outgoing feeder breaker, making a total of 50 kA. The busbar system however is only designed for an initial short-circuit current of 25 kA. At the first rise of the short-circuit current, the I_s-limiter in the bus sectionalize opens. It limits the current i_2 so rapidly that it can no longer contribute to the peak value of the short-circuit current $i_1 + i_2$ at the short circuit location. The switchgear is therefore not subjected to a higher current than that permissible at any point.

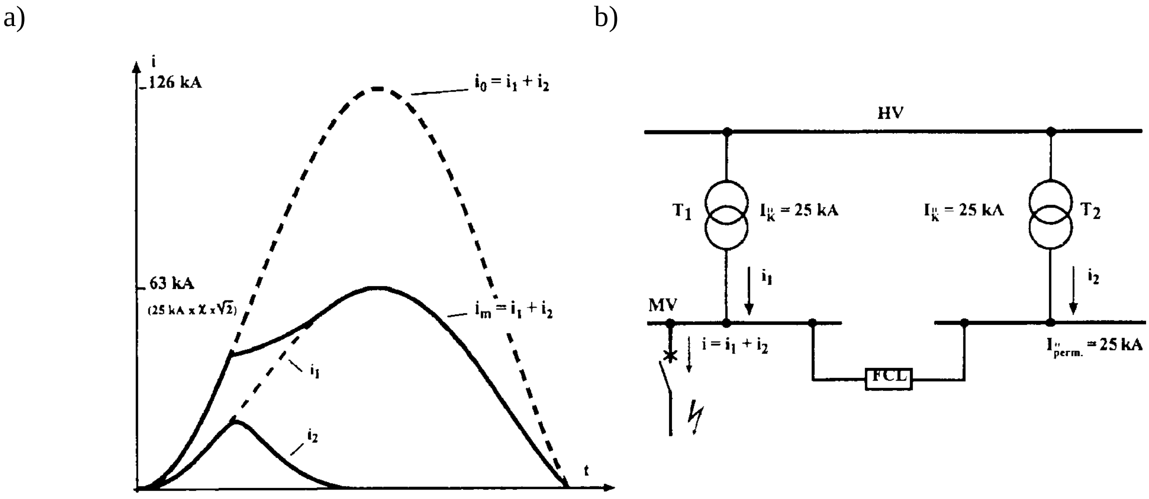

Figure A 7: Short Circuit Interruption with an I_s-Limiter

a) Current development
i_o total current without I_s-limiter
i_m total current with I_s-limiter

b) Block diagram

3.1.2.3 Resonance Links

Description

In a resonance link the voltage drop of a linear series reactor is eliminated by a series capacitor which is shunted by a non-linear bypass circuit inoperative under normal load conditions. When a fault occurs, the function of the bypass circuit is first to disrupt the series resonance condition, thus causing the series reactance to limit the fault current and, secondly to restore the load current when the fault is removed from the system.

The first reference to the use of a LC series resonant circuit for the limitation of fault currents is given in [4]. In its most simple form the resonance link consists of a circuit as shown in Figure A 8 (a). In order to ensure a satisfactory transient response of the link certain refinements have been added and these are shown in Figure A 8 (b). These refinements do not modify the general principle of operation but combine to ensure an extreme rapid overall response and to avoid possible subharmonic instability often associated with series capacitor circuits [5].

The current limitation of a fault current limiting reactor is restricted by the maximum acceptable voltage drop at full-load current. Using a resonance coupling with a series capacitor, higher values of reactance can be applied. The voltage drop at full-load current at resonance is equal to the resistive voltage of capacitor and reactor in series. To prevent unacceptable high voltages across the capacitor and the reactor during a fault the capacitor is shunted by a saturating iron core reactor. When saturation voltage of the iron core reactor is exceeded, the saturating reactor detunes the resonance condition and the impedance of the coupling increases considerably thus limiting the fault current. The advantage of such a system is the absence of moving components and its automatic restoration after a fault. Its disadvantage is the relative high cost and space demand.

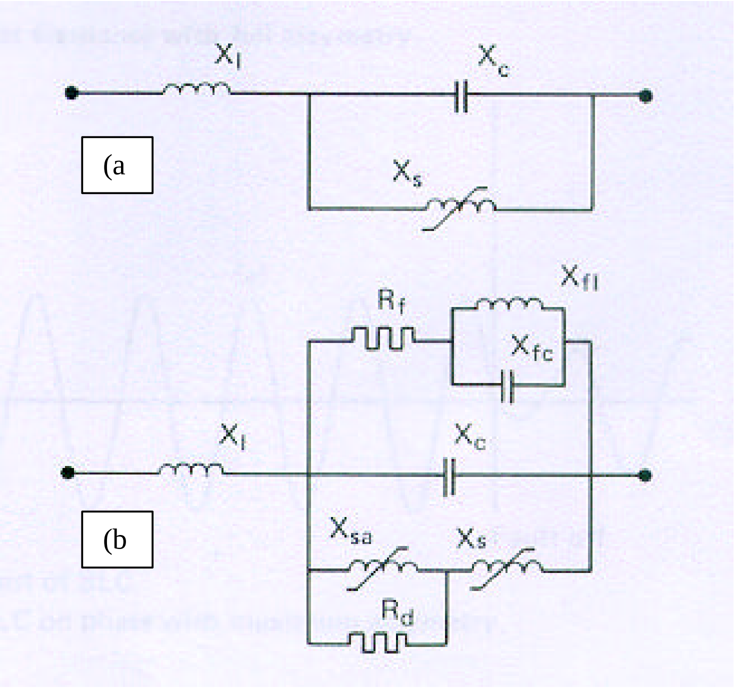

Figure A 8: Circuit diagram of a resonance link
(a) Basic circuit
(b) Refined circuit

Alternative forms of bypass circuit were also explored. Replacing the saturated reactor by a fast-acting switch, which operates on the detection of fault currents, allows greater freedom for the selection of components rating and therefore leads to the possibility of lower costs - at the complexity of introducing a switching element.

More recently the concept has been applied to series compensation schemes (refer to section 3.2.2.2).

Characteristics

• self-triggered/external triggered *)
• without current interruption
• able to carry the short-circuit current for the duration of the short-circuit
• resettable

*) depending on bypass circuit

Technical Data

In the seventies several installations have been delivered with rated currents up to 1500 A at rated voltages up to 12 kV [5]. Although the resonance links fulfil the requirements imposed on them the high cost and space demands have prevented further applications.

3.2 High-Voltage Networks (Rated Voltage: > 36 kV (40.5 kV))

3.2.1 Passive Measures

3.2.1.1 Fault Current Limiting Reactors

Description

Refer to section 3.1.1.1

Technical Data

Fault current limiting reactors are available for rated currents up to 4000 A at rated voltages up to 400 kV.

3.2.2 Active Measures

3.2.2.1 Resonance Links

Description

Refer to section 3.1.2.3

Characteristics

• self-triggered/external triggered *)
• without current interruption
• able to carry the short-circuit current for the duration of the short-circuit
• resettable

*) depending on bypass circuit

Technical Data

In the seventies several installations have been delivered with rated currents up to 1300 A at rated voltages up to 145 kV [5]. Again the high cost and space demands have prevented further applications.

3.2.2.2 Thyristor Controlled Series Compensators with Fault Current Limitation

Description

In this scheme a series capacitor is inserted in the line and a thyristor-controlled reactor is placed in parallel which, during normal operation, backs-off the capacitance, providing the required amount of line compensation (Figure A 9). The effective impedance of the line can thus be dynamically controlled which allows to increase the maximum power transfer capacity of the line. When a fault occurs, the firing angle of the thyristors is adjusted that the net impedance inserted into the line becomes inductive rather than capacitive, thus reducing the fault current. This feature is an attractive by-product of a controlled series capacitor installation [6].

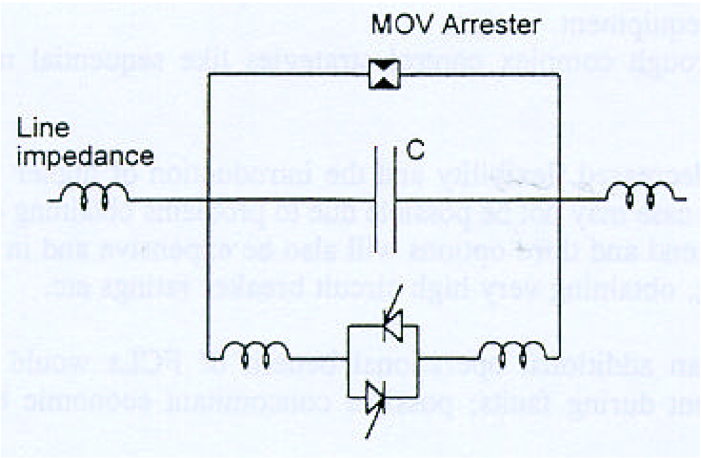

Figure A 9: Circuit diagram of a thyristor controlled series compensator with fault current limitation

Characteristics

• external triggered
• without current interruption
• able to carry the short-circuit current for the duration of the short-circuit
• resettable

Technical Data

Installations (Examples):

- 230 kV, 330 Mvar (Kayenta, U.S.A., 1992) [6]

4. Novel Approaches

In this section 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. This report therefore does not pretend to give a complete coverage of all these devices.

4.1 Superconducting Fault Current Limiters

4.1.1 Materials

Superconductivity was already discovered in 1911 by H. Kamerlingh Onnes in mercury (below 4.2 K). Nowadays more than 100 different superconductors are known.

The outstanding electrical properties of superconductors are:
- Zero resistivity below a critical temperature (T_c) and a critical current density (j_c).
- As soon as j_c and/or T_c are surpassed the resistivity of the material increases rapidly.

Most high temperature superconducting fault current limiter concepts (see section 4.1.2 to 4.1.4) exploit this sharp transition of superconductors from zero resistance at normal currents to a finite resistance at higher current densities. Fault currents are therefore limited instantly when the critical current is surpassed. Due to these features a superconducting fault current limiter comes close to the "ideal" fault current limiter behaviour of a self-triggered, fail safe device (a loss of superconductivity would result in the introduction of a high impedance in the system).

The main disadvantages of superconductors are:
- The necessity for cooling, which is rather expensive
- Superconductors tend to the development of thermal instabilities (the so called hot spots). In order to protect the materials against these hot spots often a normal conducting bypass is employed.
- AC currents cause so called AC losses which increase the cooling costs.

Low Temperature Superconductors (LTS)

The "classical" metallic superconductors have transition temperatures below 25 K. LTS wires are a commercial product for many years, also with properties which make them suitable for fault current limiter applications (high matrix resistivity, low AC losses). Accordingly, several demonstrators have been built based on LTS material (e.g. [7]). However, due to the low operating temperature (usually the material is cooled using liquid helium to 4.2 K), the cooling costs are extremely high and fault current limiters based on LTS are not expected to be commercialised. Consequently the LTS fault current limiter development efforts have been essentially stopped since the discovery of high temperature superconductors.

High Temperature Superconductors (HTS)

In 1986 a new class of superconductors were discovered. Their relatively high transition temperatures led to the name high temperature superconductors (HTS). These materials are based on copper oxide ceramics and exhibit critical temperatures up to 135 K. Therefore, most HTS materials can be operated in liquid nitrogen (77 K) which leads to significant reduction (more than a factor 10) in cooling costs. Moreover, liquid nitrogen cooling systems are far less complex than liquid helium systems.

A selection of the most important HTS materials is given below:

Family	Material	Abbreviation	Tc
La-Cuprate	La(Sr,Ba)CuO		< 40 K
RE-Cuprate	$YBa_2Cu_3O_{7-\delta}$	YBCO	92 K
Bi-Cuprate	$Bi_2Sr_2Ca_1Cu_2O_8$ $Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi2212 Bi2223	94 K 110 K
Tl-Cuprate	$Tl_2Ba_2Ca_2Cu_3O_{10}$	Tl2223	125 K
Hg-Cuprate	$HgBa_2Ca_2Cu_3O_{8+\delta}$	Hg1223	133 K

The most advanced materials with respect to industrial applications are the RE- and Bi-Cuprates (the Tl- and Hg-Cuprates are less used since they are poisonous). HTS materials can be produced as bulk (poly- or monocrystalline), thin films (on substrates) or wires (tapes). For power applications mainly Bi2223 wires, Bi2212 bulk material, and YBCO films are under consideration (flexible YBCO tapes are not yet available in large quantities).

4.1.2 Resistive Fault Current Limiters

Description

In this concept, the superconductor is connected directly to the line, which has to be protected (Figures A 10 and A 11). During a fault, the critical current of the superconductor is surpassed and its resistance increases rapidly, leading to the current limiter being quenched before the first peak value of the short-circuit current is reached. Times of less than 1 ms can be achieved between occurrence of the fault and quenching.
The device has least volume and weight compared to other superconducting fault current limiter concepts, but it requires current leads connecting the superconductor to the normal conducting line which lead to additional thermal losses. Similar to most other superconducting fault current limiter concepts, the device needs to be switched off after an irreversible quench by a conventional mechanical switch since the material heats up during the limiting phase. After some recovery time (typically in the range of a few seconds), during which the cooling medium cools the material down to operating temperature the fault current limiter is ready to resume normal operation. Special designs are also possible where the superconductor can recover to its operating temperature while carrying the nominal current immediately after the fault. However, these designs require a large amount of conductor and are therefore very expensive.

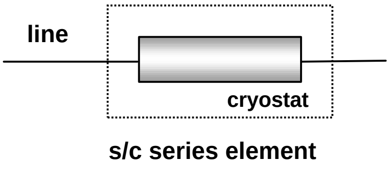

Figure A 10: Circuit diagram of a resistive superconducting fault current limiter

Characteristics

• self-triggered
• without current interruption
• unable to carry the short-circuit current for the duration of the short-circuit *)
• resettable

*) designs which are able to carry the short-circuit current for the duration of the short-circuit are feasible

Technical Data

Prototypes (Examples):

- 100 A, 7.2 kV (YBCO) [8]
- 800 A, 8 kV (Bi2212) [9]

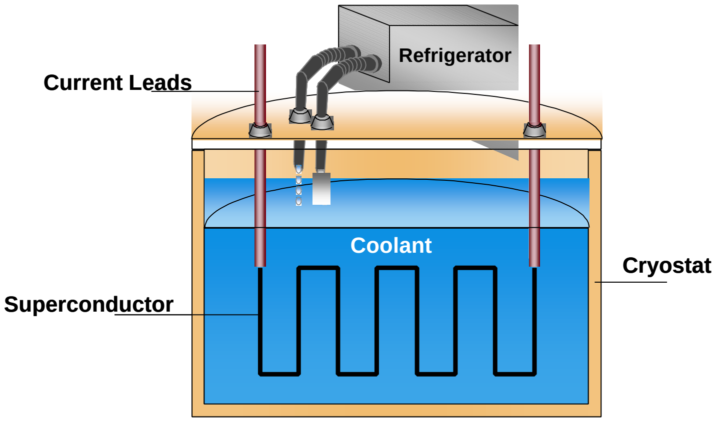

Figure A 11: Resistive superconducting fault current limiter

To illustrate the operating characteristics of a resistive type Figure A 12 shows a measurement done during the action of a 100 kVA model resistive current limiter. At time t=0 a short circuit is made deliberately and the current rises quickly according to the short circuit impedance. Exceeding the critical current I_c the superconductor becomes normal conducting (quenches) and develops considerable resistance in less than 1 ms. After the quench virtually the whole source voltage falls off at the SFCL (dashed line in Figure A 12). The current is thereby effectively reduced to even below the rated current level and is finally switched off after 45 ms. The performance of resistive type current limiter strongly depends on the type of superconductor or material used therein.

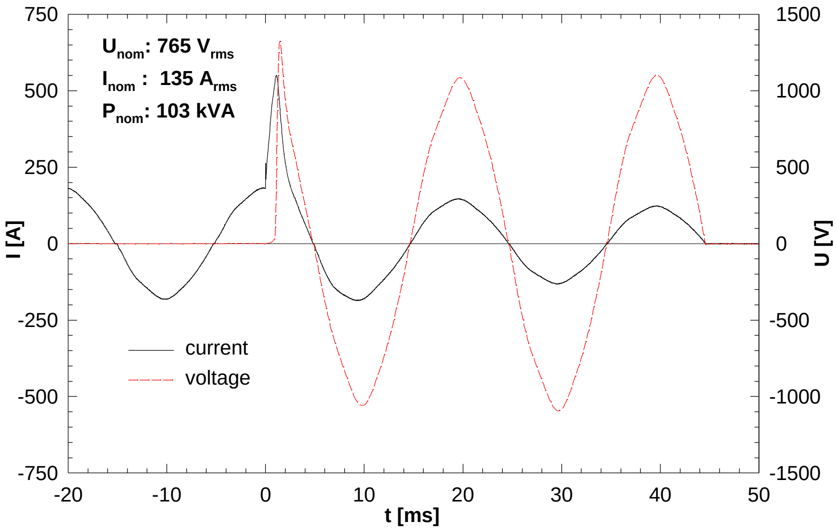

Figure A 12: Current and voltage as function as time during a 100 kVA limiting experiment

4.1.3 Shielded Iron Core Fault Current Limiters

Description

The device consists of an iron core, a primary (normal conducting) winding and a superconducting cylinder. The device can be viewed as a transformer with a shorted (superconducting) secondary winding (Figures A 13 and A 14). Because of the inductive coupling between the line and superconductor, the device is often also referred to as “inductive” fault current limiter. During normal operation the ampere-turns in the primary winding are balanced by the induced current in the superconductor (the superconductor screens the iron core). In this state the impedance of the device is very low. During a fault situation, however, the balance is destroyed (in other words: the superconductor can no longer shield the iron core), flux enters the iron and a high impedance is inserted in the line which is to be protected. The main advantages of this concept are: it needs no current leads, and since the number of turns of the secondary winding can be much smaller than the primary turns, only short superconductors are needed and the voltage drop in the cryogenic part of the device is very low. The main drawback of the concept, on the other hand, is its relatively large volume and high weight.

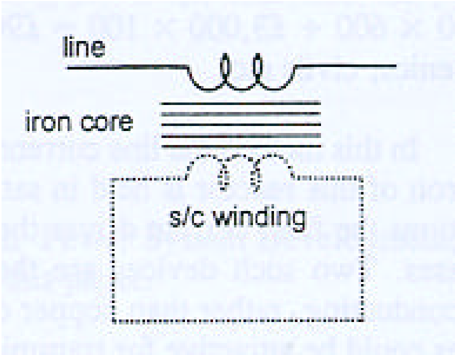

Figure A 13: Circuit diagram of a shielded iron core superconducting fault current limiter

Characteristics

• self-triggered
• without current interruption
• unable to carry the short-circuit current for the duration of the short-circuit *)
• resettable

*) designs which are able to carry the short-circuit current for the duration of the short-circuit are feasible

Technical Data

Prototypes (Examples):

- 70 A, 10.5 kV (Bi2212) [10]

The Coils of the 10.5 kV / 70 kA Prototype have 280 turns. Height and radius are 140 cm and 24 cm. The Iron-cores are made of 4 mm thick construction steel. Height and radius of the core are 190 cm and 17 cm. The effective permeability of the open core is about μ = 15. The Cryostats are based on glass-fiber reinforces epoxy with a vacuum multi-layer insulation. The Superconducting tubes consist of stacks of 16 Bi-2212 rings, each with a radius of 19 cm and a wall thickness of 1.8 mm. The total height of the stack is 140 cm.

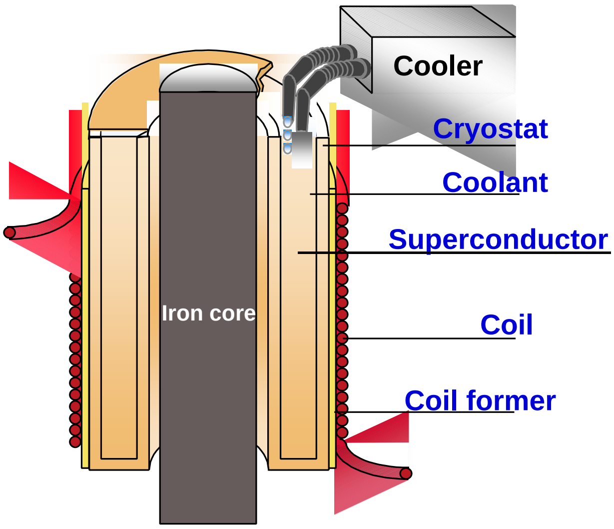

Figure A 14: Shielded iron core superconducting fault current limiter

Figure A 15 shows short circuit test results of this prototype.

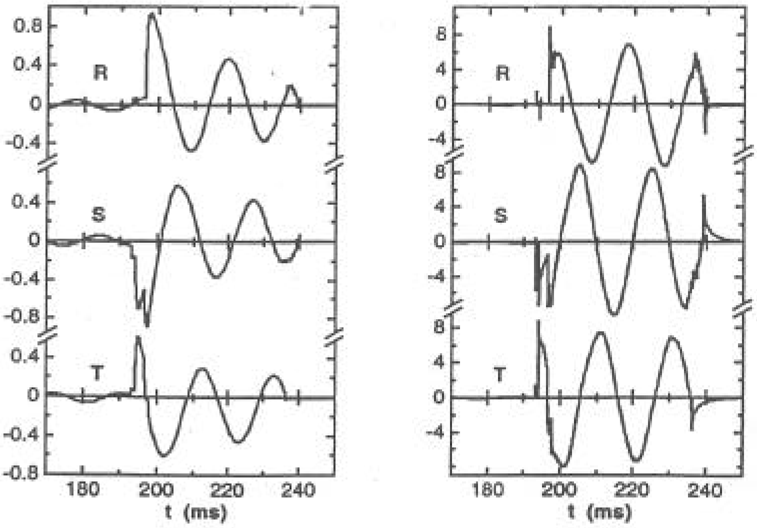

Figure A 15: Short circuit test results, current in kA (left) and voltage in kV (right).
The prospective fault current was 60 kA.

4.1.4 Saturated Iron Core Fault Current Limiters

Description

A copper coil with an iron core is inserted in the circuit. The iron core is kept in saturation during normal operation through the magnetic field of an additional superconducting winding (Figure A16). Therefore, the impedance of the device is low in normal operation. In case of an overcurrent the increased AC current through the normal conducting coil causes that the core departs from saturation. Therefore, the impedance of the device increases during a fault. The superconducting winding is exposed only to DC currents in this concept and always stays in the superconducting state so that it needs no recovery time after a fault. The main disadvantage of the concept is its large mass and volume which is about twice that of a transformer with the same power rating. There have been no larger HTS fault current limiter developments pursuing this concept so far, mainly for two reasons: a) the large volume / mass, b) the device implies relatively high magnetic fields at the superconductor. With current HTS conductors this requires an operating temperature in the range of 20 – 30 K with correspondingly increased cooling costs.

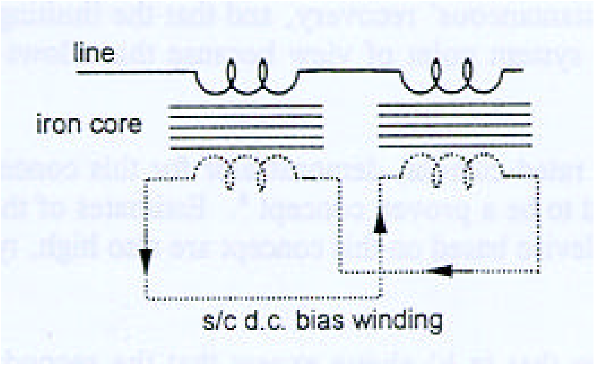

Figure A 16: Circuit diagram of a saturated iron core superconducting fault current limiter

Characteristics

• self-triggered
• without current interruption
• able to carry the short-circuit current for the duration of the short-circuit *)
• resettable

Technical Data

Prototypes (Examples):

- 556 A, 3 kV (LTS) [11]

4.1.5 "Current Controller"

Description

Apart from the above mentioned fault current limiter types, there exists a very specific concept (usually called "current controller" or "rectifier type") where the superconductor remains in its superconducting state during the fault. The device makes use of a Bi2223 coil, which has to take over the fault current as an inductive load until the actual current limitation is managed either by triggered power electronics or by a circuit-breaker in series.

Characteristics

- external triggered
- with current interruption/without current interruption *)
- resettable

*) depending on the layout of the device

Technical Data

Prototypes (Examples):

- 1200 A, 15 kV (Bi2223) [12]

4.2 Fault Current Limiters Based on PTC-Resistors

Description

A fault current limiter based on PTC-resistors consists of a current limiting element and a series connected load switch. For the current limiting element polymer composite materials are used. These composites, based on borides, silicides and carbides in a thermoset or thermoplastic matrix, show a strong PTC effect (positive temperature coefficient of resistance). The main feature of these materials is a low resistivity in the cold state and a very high resistivity in the hot state.

In case of a fault, the PTC-resistor is heated up by the fault current from the conducting cold state to the insulating hot state. Due to a very high resistivity in the hot state the PTC-resistor is able first to limit the current and second to suppress it to about zero. Further the PTC-resistor is capable of withstanding the recovery voltage for a considerable period of time. This allows the use of a simple load switch in series to the PTC-resistor.

In order to be able to use PTC-resistors as fault current limiters in medium-voltage networks an appropriate number of PTC-elements has to be connected in series. To control the voltage across these elements varistors (i.e. voltage dependent resistors) are connected in parallel to the PTC-elements. The required rated current is achieved by connecting PTC-resistors in parallel (Figure A 17) [13].

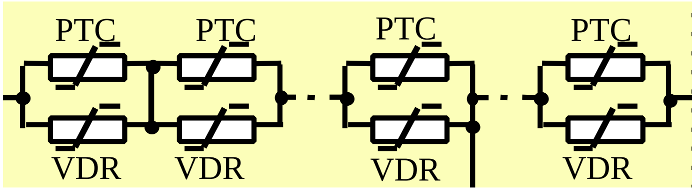

Figure A 17: Circuit diagram of a fault current limiter based on PTC-resistors

Characteristics

- self-triggered
- with current interruption (series switch)
- resettable *)

*) number of operations is limited

Technical Data

Prototypes (Examples):

- 10 A, 12 kV [13]

4.3 Liquid Metal Fault Current Limiters

Description

A liquid metal fault current limiter consists of a series wiring of individual limiting units and therefore can be adapted to applications in a voltage range up to 15 kV in principle. On the other hand this limiter is able to carry very high rated currents up to several thousands Amperes.

The principal structure of the limiting unit is shown in Figure A 18. The liquid metal fault current limiter is constructed of a number of such units. The limiting unit consists of an insulating enclosure with solid metal terminals filled with a non-toxic liquid metal alloy of Gallium, Indium, and Tin. The melting point of this alloy is 10.5 °C. Furthermore the vapor pressure is very low and no detrimental effects on human beings are to be feared. The device features a sealed enclosure and is maintenance-free. The dimensions are comparable to classical circuit-breakers of the same rated current. In order to reduce pressure peaks inside the enclosure during fault current interruptions the device is not completely filled with liquid metal.

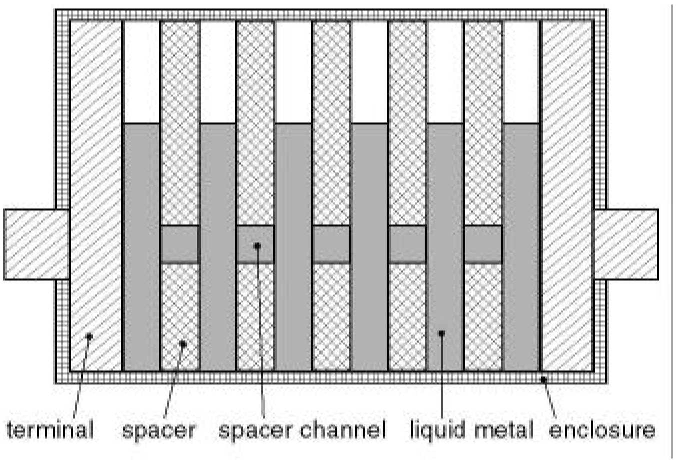

Figure A 18: Principal structure of a limiting unit of the liquid metal fault current limiter

The cavity is subdivided by several insulating spacers which constrict the current path through a hole. The main functional element of this design is the stricture-spreading sequence of the spacer channels which causes a strongly non-homogeneous current density distribution. This triggers the self-magnetic pinch effect. The pinch-off is made possible by the fluidity of the liquid metal and results in initiating arcs in each spacer. A high arc- voltage build-up is obtained due to the series wiring of the spacer channels. This corresponds to the arc splitting method in classical low voltage current limiting devices. By using an adequate number of units the liquid metal fault current limiter is able to limit fault currents in medium-voltage networks. The fault affected branch must be disconnected by a series-connected switching device. The liquid metal fault current limiter is self-healing, i.e. it returns to standby condition, because the liquid metal flows back into the channels and closes the current path [14].

Characteristics

- self-triggered
- without current interruption
- unable to carry the short-circuit current for the duration of the short-circuit
- resettable

Technical Data

Prototypes (Examples):

- No prototypes have been realised so far for medium-voltage or high-voltage applications

4.4 Solid-State Fault Current Limiters

Description

Solid-state fault current limiters consist of semiconductor devices which are able to interrupt a fault current during its rise before the peak value is reached. For this purpose self-commutated solid-state devices like GTOs (Gate Turn-off Thyristor), IGBTs (Insulated Bipolar Transistor) or GCTs (Gate Commutated Thyristor) are used. In principle it is also possible to use thyristors together with a commutation circuit. Especially well suited for medium-voltage applications is the GCT which features very short operating times of only a few microseconds. It is also available as integrated version (IGCT) with the gate unit on anode potential.

An example of a solid-state fault current limiter is shown in Figure A 19. It consists of a bi-directional semiconductor switch (two semiconductor devices arranged in inverse parallel), in parallel to which a current limiting impedance is connected (in the given case the semiconductor switch consists of GTOs and the current limiting impedance is a reactor).

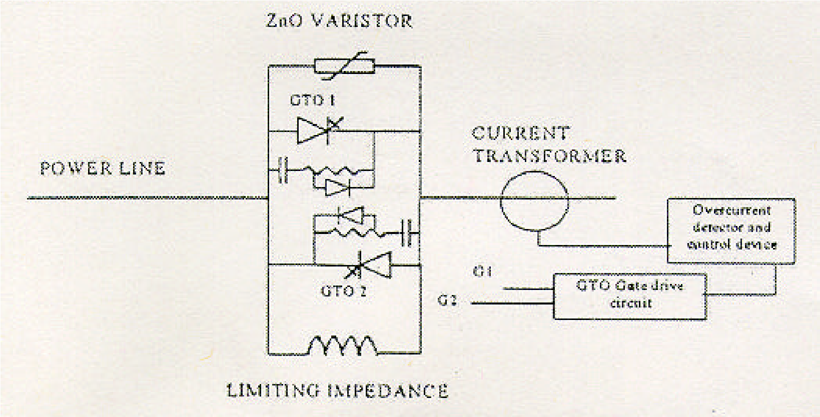

Figure A 19: Circuit diagram of a solid-state fault current limiter with limiting impedance

When a fault is detected, the normally conducting semiconductor switch is turned off and the current is diverted into the current limiting impedance which limits the fault current. In parallel with the semiconductor switch there is a surge arrester (ZnO varistor) and a snubber circuit to limit the amplitude and the initial rate-of-rise of the transient voltage across the semiconductors.

Figure A 20 shows a circuit line diagram of a solid-state fault current limiter without limiting impedance [15]. In this case the semiconductor switch is turned off very fast before the fault current reaches the peak.

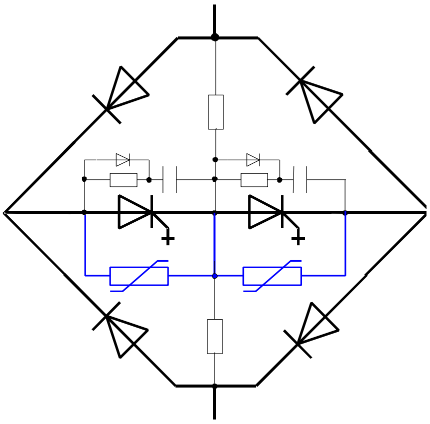

Figure A 20: Circuit diagram of a solid-state fault current limiter without limiting impedance

With solid-state devices it is possible to realise both ultra-fast current limiting switches (interrupting time a few milliseconds) and fault current limiters which are able to sustain the limited fault current as long as necessary for a conventional circuit-breaker to clear the fault. The main drawbacks of the solid-state current limiter are its cost and losses.

Innovative Solutions in FACTS technology can also be applied for a new dynamic short-circuit current limiting device, the SCCL. This new device operates with zero impedance in steady-state conditions, and in case of a short circuit it is switched within a few ms to the limiting-reactor impedance (Figure A 21).

In series compensation, a capacitor is used to compensate for the line´s impedance, thus the line is "virtually" shortened and the transmission angle decreased for system stability improvement. However, during transient conditions, the short-circuit currents cause high voltages across the capacitor, which must be limited to specified values. In the past, this limitation was accomplished by arresters (MOV), by a spark gap, or in a combination of both. The (mechanical) gap function can now be replaced by an innovative solution with high power thyristors, which are designed and tested for a 110 kA peak current capability for a sufficiently long time.
By combining the TPSC with an external reactor, whose design is determined by the allowed short-circuit current level, this device is highly suitable to be used as a short-circuit current limiter (SCCL).

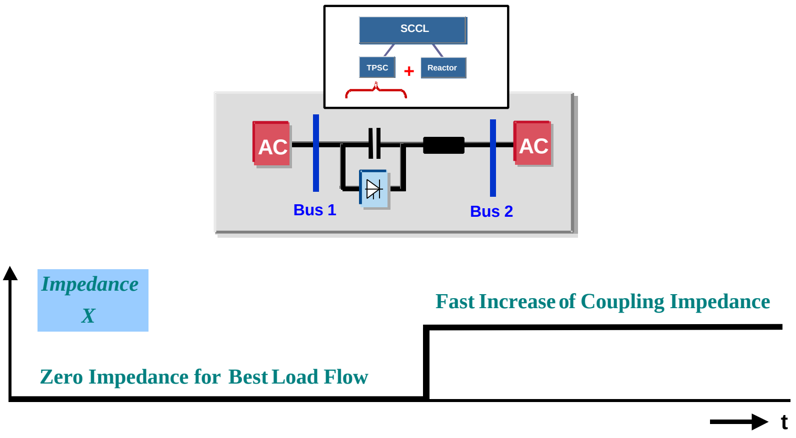

Figure A 21: SCCL - Fast Short-Circuit Current Limitation with high power thyristor

Recordings from site measurements of real faults and simulations of the fast acting current-limiting function have shown: This new type of SCCL achieves a high speed limiting function very similar to the superconducting HTS Fault Current Limiter element.
The design of the SCCL focuses on maximum Reliability and Availability.
A significant benefit of this new FACTS device for dynamic short-circuit current limitation is the possibility of a highly flexible system expansion, including system interconnections and new power plants, due to the zero impedance in steady-state conditions: there is no change in load-flow and no reduction of stability.

Characteristics

• External triggered
• with current interruption/without current interruption *)
• able to carry the short-circuit current for the duration of the short-circuit **)
• resettable

*) depending on the layout of the device
**) device without current interruption

Technical Data

Prototypes (Examples):

- 500 A, 13.8 kV
- The SCCL is based on developments in series compensation, where the TPSC (Thyristor Protected Series Compensation) has been successfully applied on 3 projects in a 500 kV transmission system in the Southern Californian Grid (USA), at the Vincent substation.

4.5 Fault Current Limiters Using Electromagnetic Forces

4.5.1 "Driven-Arc" Type

Description

In the "driven-arc" type fault current limiter an arc is generated between narrow parallel resistive conductors which inserts resistance into the circuit automatically and thus limits the fault current. The fault current limiter consists of transfer resistors, a high-speed switch and rotary arc type circuit-breakers which are mounted in a sealed chamber (Figures A 22 and A 23).

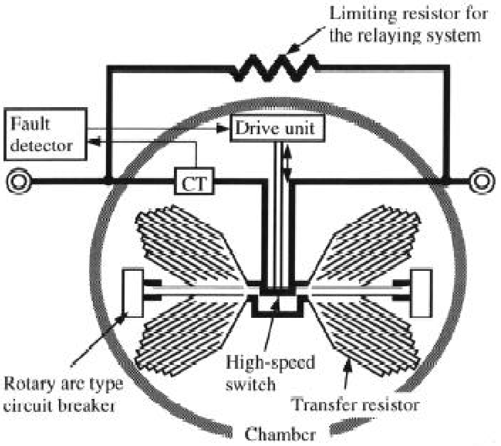

Figure A 22: Arrangement of a "driven-arc" type fault current limiter

Figure A 23: Driven-arc type fault current limiter

Characteristics

• external triggered
• with current interruption
• resettable

Technical Data

Prototypes (Examples):
- 400 A, 7.2 kV [16]

4.6 Hybrid Fault Current Limiters

Description

A hybrid fault current limiter consists of a combination of different modules. Each of these modules has to fulfil a certain task during the operation of the device. Figure A 24 presents the principle of a hybrid system. Figure A 25 shows the concept of a realisation of a hybrid current limiting device with three parallel paths.

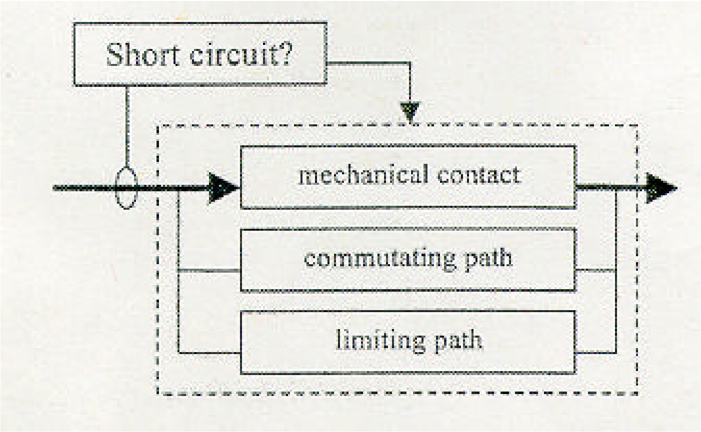

Figure A 24: Principle of a hybrid system

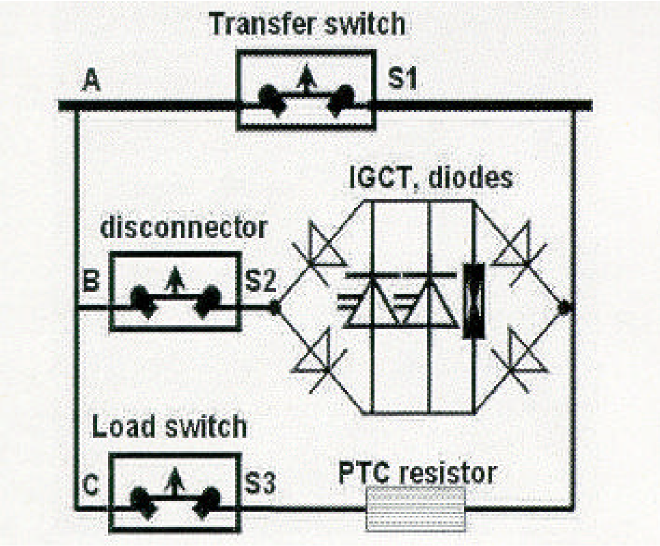

Figure A 25: Circuit diagram of a hybrid fault current limiter

A short-circuit detection unit monitors the current and triggers the device in case of a fault. Then an ultra-fast mechanical contact (transfer switch), which is designed to carry the nominal current, is opened within several 100 µs by means of an electro-dynamic repulsion drive and commutates the still rising current into the commutation path. This path consists of an arrangement of semiconductor devices (IGCTs, diodes and surge arresters) connected in series with a very fast switch, serving as a disconnector. The IGCT provides a time delay for the transfer switch to recover to a certain withstand voltage and is switched off subsequently, forcing the current into the limiting path. This path consists of a low-inductive non-linear resistor with PTC-characteristics. Before this resistor is heated up significantly, thus limiting the current, the disconnector is opened so that the semiconductors are isolated from the further rising voltage. Finally, the load switch with an opening time of less than half a cycle interrupts the fault current at its first zero crossing. The time delay between detection of the fault and the limitation of the current is less than 1 ms [17].

Characteristics

• external triggered
• with current interruption
• resettable

Technical Data

Prototypes (Examples):
- 2000 A, 12 kV [17]

5. Conclusions

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.

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A detailed list of literature is enclosed as part E within this Technical Brochure.

Part B

Functional Specification for a Fault Current Limiter

B Functional Specification for a Fault Current Limiter

1. Introduction

What is a Fault Current Limiter? Simply stated a FCL is a device which, on the occurrence of a fault, limits the current in a crucial branch of the circuit so that no component in the system becomes overloaded. Series reactors have performed this function for many years, but they have a serious disadvantage in that they produce significant I^2R losses.

The specification of a piece of electric power equipment, as we now know it, is a detailed list of requirements covering a wide range of subjects. It is usually negotiated between the purchaser and the vendor. It is impossible at this time to draw up a general specification for FCLs inasmuch as with one notable exception, they do not exist, or at least they are not available commercially. What the report does is point out the critical features that must be addressed when considering the design for a specific application.

2. Applications for Fault Current Limiters

2.1 Fault Current Limiter in the Coupling

Instead of designing the two systems for the total short-circuit current, FCL is installed in the coupling. In case of a fault, it reduces the peak short-circuit current at the very first current rise.

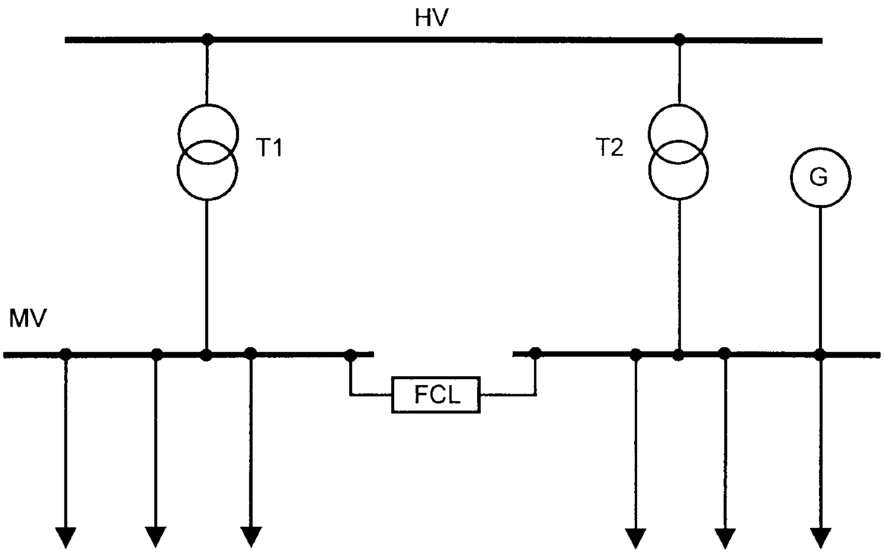

Figure B 1

Advantage of this application:

- By parallel connection of transformers (two systems) one will get an even distribution of the feeding transformers.
- Reduction of the required short circuit capability of the system.
- Reduction of the network impedance.
- No disconnection of the feeding transformers after tripping of the FCL.

2.2 Fault Current Limiters in the Incoming Feeders

Instead of designing the system for the total short-circuit current, a FCL is installed in the incoming feeder(s). Also in this case if fault occurs, each FCL will reduce the peak short-circuit current at the very first current rise.

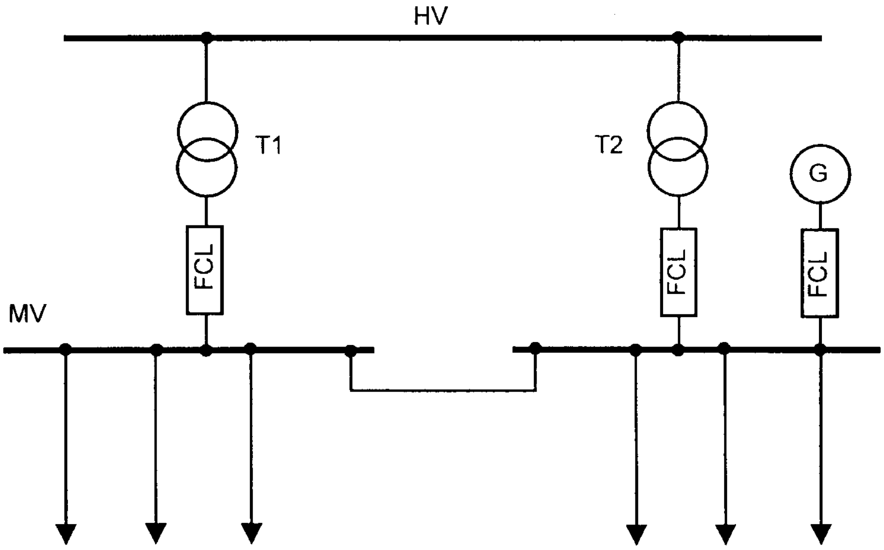

Figure B 2

Advantage of this application:

- By parallel connection of transformers (two systems) one will get an even distribution of the feeding transformers.
- Reduction of the required short circuit capability of the system.
- Reduction of the network impedance.
- The short-circuit current of the feeding sources (transformers and generator) will be reduced.

2.3 Fault Current Limiters in the Outgoing Feeders

Instead of designing the sub-systems for the total short-circuit current, a FCL is installed in each outgoing feeder. Also in this application in case of a fault, each FCL reduces the peak short-circuit current at the very first current rise.

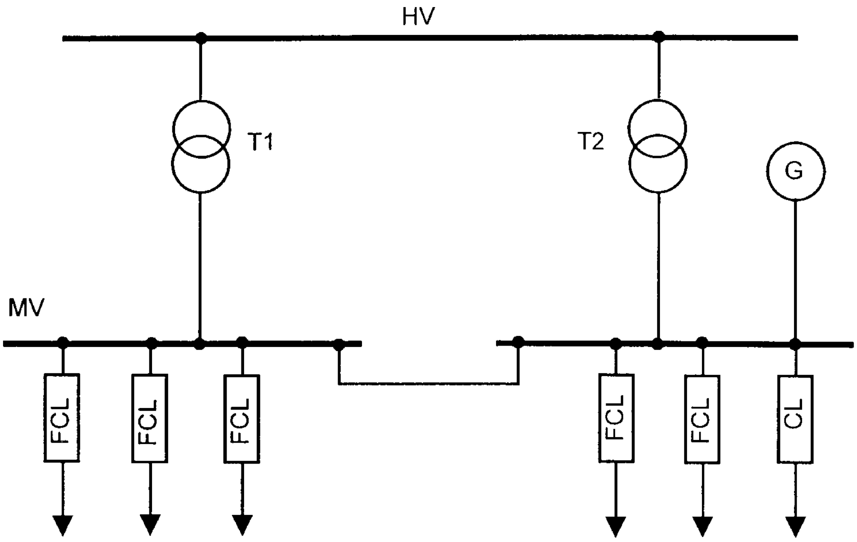

Figure B 3

Advantage of this application:

- By parallel connection of the transformer (two systems) one will get an even distribution of the feeding transformers.
- Reduction of the required short circuit capability of the sub-systems.
- Reduction of the network impedance.
- In each outgoing feeder a FCL is installed. By doing this only the short-circuit current flowing to the faulty outgoing feeder will be reduced. The main bus must be designed to carry the total short-circuit current.

2.4 Fault Current Limiters in Parallel to a Reactor

In all above mentioned applications the FCL can be installed in parallel to a reactor.

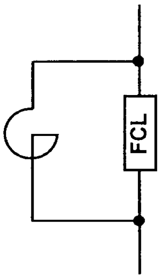

Figure B 4

In this case the disadvantages of the reactor will be avoided. In general the reactor has got the following disadvantages:

- Current dependent copper losses and the associated operating costs of the reactor.
- Current dependent voltage drop at the reactor, which frequently causes major difficulties on start-up of big motors.
- Control problems with the generator.
- Current dependent noises of the reactor.
- Electro-Magnetical-Compatibility

3. System Device Interaction of the Fault Current Limiter

It can be expected that there will be interactions between the FCL and the system when the FCL is placed in the system. This section does not represent a full investigation of these interactions nor the impact of these interactions on system and device performance. Rather it lays the groundwork for an investigation.

3.1 Effect of a Fault Current Limiter on the System

3.1.1 Effect of a Fault Current Limiter on the Protection Scheme

The fault current limiter can affect the system at the following levels:

- Selectivity (time coordination between over-current relays)
- Relay settings (incoming feeder, outgoing feeder, customer side, etc.)
- Protection blinding (directionality) in the presence of a private generator
- Compatibility with downstream fuses

Whatever the location of the FCL, the above issues should be analyzed for any possible location of the fault:

- Fault on a feeder feeding a private producer
- Fault on an adjacent outgoing feeder
- Fault on the incoming feeder
- Fault on the customer internal network
- Fault on the busbar
- etc.

3.1.2 Impact on an Independent Power Producer Installation

- impact on the generator stability
- impact on generator decoupling protection

3.1.3 Effect of the Fault Current Limiter on the Network Conventional Switchgear

- Transient Recovery Voltage of the downstream circuit-breakers

3.1.4 Impact on the Overall Reliability of the System

- RAMS of the fault current limiter
- Failure mode of the fault current limiter in case of an internal fault (short-circuit/open-circuit)
- Effect of a no-trip when tripping is required.
- Effect of trip when no trip is required.

3.2 Effects of the System on the Fault Current Limiter

3.2.1 Undesirable tripping

Undesirable tripping of FCLs can be caused by transient phenomena in the network:

- Capacitor banks switching
- Downstream Transformer energization
- Starting of big motors
  can generate high current values likely to
  lead to undesirable tripping of the current limiter.

3.2.2 Ability to Sustain Short-Circuit Currents

Here we make a difference between a current limiter actually meant to break the fault current (I_s limiter, solid-state current limiter) and a current limiter whose function is only to limit the fault current at a chosen value until the conventional electromechanical circuit-breakers eliminate the fault (superconducting fault current limiter or I_s limiter in parallel with a reactor).

In the second case the fault current limiter, well suited to match the over-current protection scheme selectivity of a radial network, must be able to sustain the short-circuit current as long as necessary, during the more constraining reclosing cycles programmed in the protection scheme.

4. Functional Specification for a Fault Current Limiter

For fault current limiters (FCLs) to be used in electrical networks, their characteristics have to be defined. The characteristics described within this specification are derived from the characteristics of circuit breakers and fuses and will give some criteria of how to define the behavior of limiting devices in general, independent from the different possibilities of their operation characteristics or technical realization.

Therefore this specification presents some more general characteristics and relations which will contain the different behavior of still existing limiting devices (e.g. limiting reactors, I_s-limiters) as well as limiting devices which are under development for future operation in electrical systems (e.g. superconducting fault current limiters, solid-state fault current limiters).

The aim of this specification for a fault current limiter is not to specify in detail the rating of a fault current limiting device to be manufactured, but furthermore, to define the basic characteristics and relations which can be handled from users and manufacturers, if they have to describe the limiting behavior needed in an electrical system.

Figure B 5 shows the unlimited short circuit current initiated at t = 0 and the current limiting function of different FCL devices.

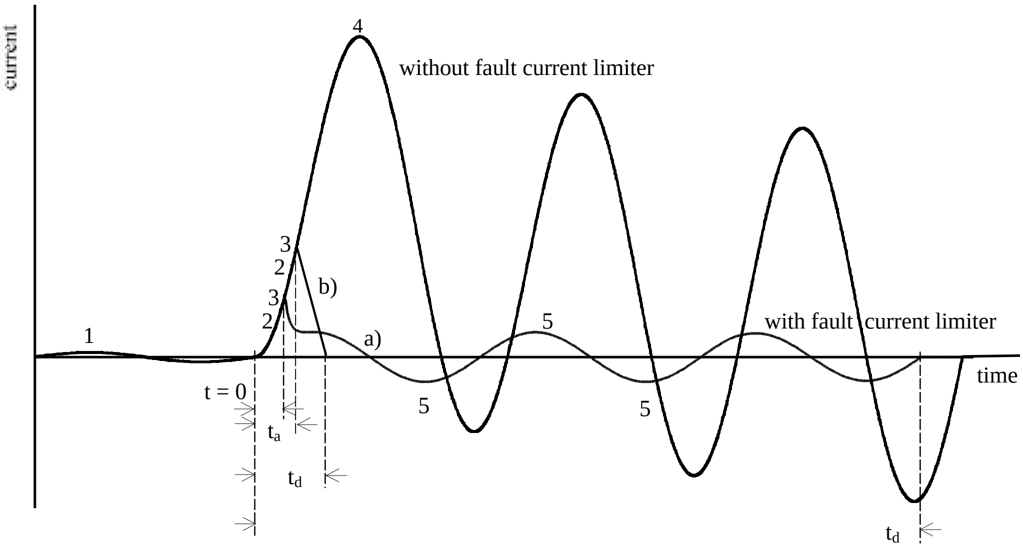

Figure B 5: Short circuit current initiated at t = 0 without any limitation and with
a) superconducting fault current limiter
b) pyrotechnic fault current limiter

The following definitions describe a fault current limiting device in general (denomination, see Figure B 5):

normal operation:
rated system voltage (U_n)
1: √2 rated current (I_n)

limitation:
2: minimum initiating current ($\hat{\imath}_{min}$)
3: maximum limited current ($\hat{\imath}_{max}$)
4: peak short circuit current ($\hat{\imath}_p$)
5: peak value of the follow current ($\hat{\imath}_{fol}$)

The performance characteristics of FCL devices can be described using the following relations:
η_0: follow current ratio
(ratio of peak value of the follow current (5) to peak value of rated current (1))

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

η_2: current limiting ratio
(ratio of peak value of the follow current (5) to 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
(time defined from fault initiation at t = 0 to fault current interruption)

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

I^2 x t: pre-arcing I^2 x t

5. Questionnaire

5.1 Introduction

An early undertaking of Working Group A 3.10 was to prepare a questionnaire that was sent to companies in seven countries, requesting their input. The principal purposes were to determine how familiar the recipients were with the notion of current limiting and to try to assess how the perceived need for such devices. Most, but not all of these companies were electric utilities, some were industrial users of power. The questionnaire was accomplished by a short description of how an FCL might operate. In the continuing section, the question will be given first, followed by the response.

5.2 Responses to the Questionnaire

The Questionnaire contained eleven questions; the responses will be summarized in the order in which the questions were asked.

5.2.1 What voltage levels in the range 12 kV – 145 kV do you have on your system?
Please respond in order of prevalence, e.g. 12 kV – 40 %, 72 kV – 25 %, etc.

Using the ranges specified in the Questionnaire, the results are as follows:

12/15 kV*	26/69 kV	115 kV
67.8 %	29.9 %	2.3 %

*voltage below 12 (e.g. 6 kV) were put in this category.

5.2.2 Have you ever applied current limiters?

Of the sixty-five companies responding to this question, twenty-six said yes, and thirty-nine said no. Those in the affirmative were mostly industrial users which had a specific current limiter (the ABB I_s - Limiter) in service. A very small number of respondents said that current limiting was not an issue on their systems. Most indicated that they were unaware of solutions, the remainder believed that the solutions available were uneconomical for their systems.

5.2.3 At what voltage level(s) would an FCL be most useful in your system?

The overwhelming number (56) of responders identified the low/medium voltage range (4 - 13.8 kV), three chose 69 kV, four chose 138 kV and one chose 362 kV (this latter level is outside the inquiry).

5.2.4 Rank in importance the three applications denoted in the Questionnaire.

The rankings showed a clear preference for the bus tie application:

• bus tie location or bus coupler	71%
• in transformer feed	19%
• in individual feeds	10%

5.2.5 What degree of current limiting do you believe in the voltage level(s) you have identified? ((a) desirable, (b) acceptable)

There appear to be two definitions of „degree of current limiting“. Both define it as

$$\frac{\text{current with limiter operation}}{\text{current without limiter operation}}$$

The first definition refers to the current in the short circuit and is perhaps most useful from a user’s point of view. The second refers to the current through the current limiter and is perhaps more useful from the point of view of the designer of the device. If the current limiter is moved from one location to another in the system, the degree of current limiting according to the first definition may change, but not according to the second. The first can be said to be „location specific“. The second definition is „device specific“. The responses indicated that the respondees did not understand the question or had not thought it through. Responses varied from „limit to 2 kA“ and „1.5 x“, to 20 %, surely a very wide range. There is a clear need for educating the customer so that he does not make unreasonable (and probably unnecessary) demands.

5.2.6 What would you consider acceptable losses and volt drop with normal load current?

Many respondents gave similar answers to both of these questions „less than a reactor“, or „no more than a reactor“. When figures were quoted the center of gravity appeared to be 2% or less, though 2% of what is not clear. About 20% would accept losses in the range of 2% to 5%. The data on volt drop was very similar, i.e., the majority favored 2% or less, but about 20% would accept higher losses (up to 5%).

5.2.7 Do you have any specific requirements on the way FCL should operate (I_L/I_A, I_L/I_C, I_L/I)?

This question had little interest, most respondents implied that it did not matter. There was no consensus among those who offered an opinion.

5.2.8 What location(s) in your system would be most useful to your operation?

The data was as follows:

Substation	Substation Transformer	Bus Tie	Feeder	Generator Output
10.4 %	16.4 %	46.3 %	13.4 %	13.4 %

5.2.9 What would be the operating cycle of an FCL?

The majority clearly felt that FCL’s need not have all the attributes of a circuit breaker with respect to duty cycles. The results were:

Instantaneous Open	OCO	O-3$_s$-CO-15$_s$-CO	O CO CO
74.2 %	9.7 %	8.1 %	8.1 %

5.2.10 How many operations would you expect before maintenance or repair?

There was more spread on this question, indicating a range of expectations.

Less than 5	5 - 10	10 - 20	20 – 30	30 - 50	More than 50
59 %	0.6 %	6.1 %	6.1 %	4.5 %	13.6 %

A large fraction of those who expected to serve the FCL after every operation already have a type of FCL in service which requires this kind of maintenance. This fact of experience gives a bias to the data.

5.2.11 Clearly the price of fault current limiter will affect its appeal to a potential user. Please give an indication of its worth to you. E.g., as xy (cost of conventional circuit breaker).

The range was wide, from xy = 0.25 (!) to xy=10. Details are

Equal or less then CB	1 - 3 CB	3 - 5 CB	5 - 10 CB
11.3 %	22.6 %	17 %	49 %

6. Conclusion

This report has produced what its title proclaims, a Functional Specification for a Fault Current Limiter. It has laid out the essential parameters that must be defined for a specification.

There is a clear indication from the Questionnaire that there is an interest in FCLs, especially at the distribution voltage level. It is important that potential users become acquainted in more detail with the technologies being investigated and the capabilities of the products being developed. Helping to bring this about, should be an important task of Working Group A3.10. The Electric Utility Industry has traditionally been conservative. Frequently, when new products have been offered, the response has been, „What experience do you have?“, to which the reply is usually, „None yet, it’s a new product“. The discussion then concludes with, „Come to see us again when you have some experience“. Perhaps the experience gained by industrial users will help in this instance.

Part C

Fault Current Limiters - System Demands

C Fault Current Limiters - System Demands

1. Introduction

The management of power systems in countries in all parts of the world is now changing and there is a strong tendency towards separating generation from the primary transmission grid. In this deregulated environment the power utility responsible for operating the primary grid loses control over the siting and scheduling of generation.
Therefore, large concentrations of generation can be developed in areas where previously little generating plant existed.
Connection of independent power producers to the basic network causing the increase of short-circuit levels not included in previous long-term planning forecasts will require more and more knowledge of techniques for short-circuit limitation both at high-voltage (HV) and at medium/low-voltage (MV/LV) levels of the existing network.

This makes the limitation of the fault current level an important issue, which is now being investigated by electric utilities, universities, researchers and manufacturers.

The following document presents the first experience and the demands of several utilities located in Brazil, France, Germany, UK, Canada, US, Korea and Japan.

2. Installation locations for fault current limiters

Installation locations for fault current limiters are characterised by the type of location and the voltage level. The types of location are typically in a substation between two busbars, that could be its most common use in the future, or in series with a feeder connected to a busbar, or in series with the equipment to be protected.

Further detailed installation locations are presented in section 5. "Utilities experience".

3. Requirements for fault current limiters

The main features required for the installation of a fault current limiter are:

- ⇨ Impedance: it must be as low as possible in normal operation, in order to prevent:
  - resistive losses
  - reactive losses
  - voltage drop

- ⇨ Ratings : three ratings must be considered:
  - normal operating condition
  - over-load condition
  - short-circuit:
    - prospective / limited current
    - over-voltage during operation
    - operation speed
    - transient phenomena
    - recovery time after operation
    - ability to perform multiple operations

- ⇨ Protection
  - Selectivity
  - interaction with existing protection plan or concept
  - interaction with new/future protection concepts
  - limits damaging fault energy thereby providing a
  - safer working environment for personnel

- ⇨ Safety & impact on environment
  - electrodynamics interference (in case of use of reactors in parallel)

- ⇨ Lifetime & maintenance

- ⇨ Cost (installation, operation, life cycle cost,...)

- ⇨ Reliability: FCL design must ensure a high level of reliability (FCL will operate even after long durations between events)

4. Benefits of the insertion of a fault current limiter

FCL benefits concern not only grid equipment protection, but also power quality: by coupling busbars, short circuit power of several sources are added.

- ⇨ Improve power quality
  - reduces voltage sags, flicker
  - reduces harmonics
  - temporary over-voltage (e.g. due to connection of IPP)

- ⇨ Avoid high investments and over-dimensioning of equipment

- ⇨ Avoid follow-up costs

5. Experience considering utilities' different applications

5.1 Utility A: Furnas Centrais Elétricas S. A. - Brazil

5.1.1 Introducing FURNAS

Furnas Centrais Elétricas S. A. is a power utility for generation and transmission, responsible for the supply of bulk energy to the Brazilian south-eastern region. The voltage levels at FURNAS transmission system are 765 kV, 500 kV, 345 kV, 230 kV and 138 kV (AC) and ±600 kV (DC), all of them classified as high-voltage ***(HV)***, resulting in approximately 17500 km of high-voltage transmission lines. There is also a low-voltage ***(LV)*** level at FURNAS system which is the 13.8 kV voltage supply for the auxiliary services at the transmission substations.

5.1.2 Long-term experience

A common practice in many Brazilian power utilities, including FURNAS, a typical ***(LV)*** application, is the usage of air-core series reactors ***(Current Limiting Reactors -> CLR's)*** at the tertiary windings of auto-transformers. Limitation of short circuit levels is needed since, due to system requirements of small values of H-L impedance for auto-transformers, short-circuit levels at tertiary (auxiliary services / rated voltage = 15 kV) result higher than the switchgear capacity. Disadvantage effects like high voltage drops, joule losses and magnetic fluxes, which could even make the ***CLR*** application unfeasible, cause practically no effect to the performance of the high-voltage transmission system.

Characteristics of 15 kV CLR's installed at some of FURNAS substations are shown in Table C 1.

FURNAS Substation	Inductance (µH)	Rated Current (A)	Volt Drop (%)	Maximum Losses ≤ 0.5% (kW)	Rated Short-Circuit Current (kA)	Short-Circuit Limitation	
						From (kA)	To (kA)
ADRIANÓPOLIS	273	2000	2.4	2	40	44	29
FURNAS	4213	272	5	0.6	5.4	15	4
GRAJAÚ	1061	1083	5	2.3	25	124	17
JACAREPAGUÁ	598	1924	5	4.2	39	40	20

Table C 1: Characteristics of 15 kV CLR's

5.1.3 Recent experience

Two Brazilian power utilities have adopted the usage of CLR's at the primary transmission grid, in series with transmission lines, at voltage levels of 145 kV (CEMIG - middle eighties) and 362 kV (FURNAS - Dec. 1998), in order to bring fault current levels down to the existing equipment ratings.. FURNAS case would be the first CLR application in Brazil at 362 kV. Important aspects like the transmission system performance under steady-state and transient conditions, the definition of the physical dimensions for the equipment, the specifications of the electrical characteristics and the special cares with respect to magnetic flux generated by the CLR have been investigated for these typical ***(HV)*** cases.

The following electrical characteristics have been specified for FURNAS 362 kV CLR:

Rated voltage (kV):	362	Rated short-circuit current (kA, rms) :	25
Rated frequency (Hz):	60	Basic Insulation Level (kV, crest) :	1300
Per phase inductance (μH):	24000	Basic Switching Level (kV, crest) :	850
Rated current (A):	2100	Quality factor:	>200
Max. allowed volt. drop (kV, rms):	18.9	Installation type:	outdoor
Rated power (MVAr):	40		

Table C 2

The one-line diagram of the network below, shows two CLR's installed in series with the transmission lines coming from ITAPETI to MOGI 345 kV substations:

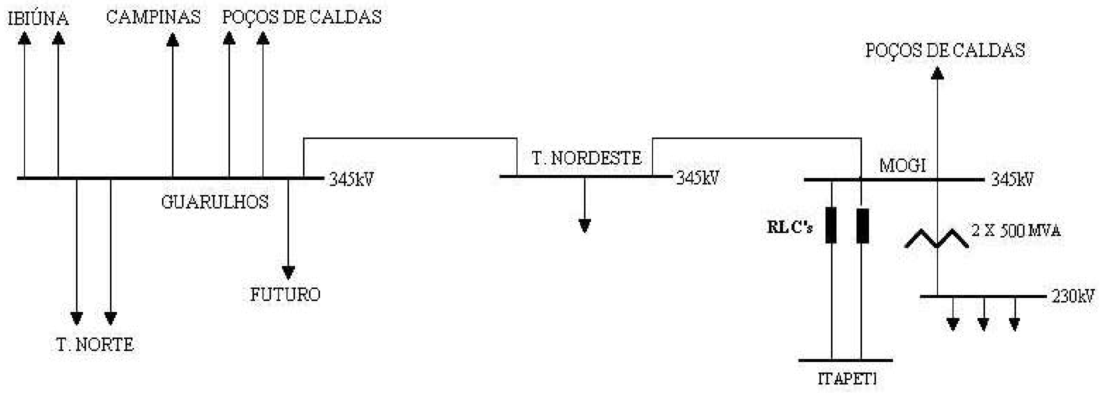

Figure C 1

The economic savings of this limitation in short-circuit level, computing only 362 kV equipment that would have to be substituted by new ones, were estimated around US\$ 10 x 10^6. This evaluation did not consider the needed reinforcement for the busbars, ground grid and structures at the switchyard.

5.1.4 Future needs

Following the tendency of many countries in the world, management of power systems in Brazil is also changing towards separating generation from the primary transmission, making the limitation of the fault current levels a more important issue.

There are several new thermal power plants planned to be installed for the next years, several of them in Rio de Janeiro state, causing strong impacts on FURNAS's existing network. For cases, where the CLR solution has appeared to be unfeasible, preliminary systems studies have proposed to split busbars at both FURNAS's and the thermal power plant substations, but it is far from the ideal solution since it reduces reliability. Other solutions should be investigated since the existing network cannot wait anymore for long-term studied solutions, but immediate ones.

5.2 Utility B: Electricité de France - France

5.2.1 Introducing Electricité de France

Electricité de France (EDF) is the French national power utility for electricity production and distribution. For a few years, EDF is developing a new strategy in the framework of an international group, through its industrial investments in emerging countries, by extending its range of energy and service offers via specialised subsidiaries and by means of rapid development within its new internal market, Europe.

The total production in France is nearly 500 TWh/year (nearly 80% from nuclear power).
The transmission network is divided in several voltage levels: 400 kV, 225 kV, 90 kV, 63 kV and operated by French TSO.
The distribution network is mainly 20 kV and 400 V.

The usually admitted short-circuit currents are:

Substation voltage	20 kV	63 - 90 kV	225 kV	400 kV
Max short-c. current	12.5 kA	31.5 kA (20 kA)	31.5 kA	63 kA (40kA)

Table C 3

5.2.2 EDF experience in current limitation and grid protection

Until today, EDF does not use Fault Current Limiters (FCL); all equipment is designed to withstand full fault current. Faults in the grid are eliminated by circuit breaker opening or recloser cycles, initiated by protections, that are defined in a ***protection plan***. These configurations are very specific to the voltage level, but are all the same in France.

The devices used by EDF for the grid are protection circuit breakers and reactors. However, FCL may be an interesting option in the context of future evolutions in the network and its connected generators.

5.2.3 EDF grid evolution, market deregulation and opportunities for Fault Current Limiters

The recent European trend to deregulation will have a strong impact on EDF grid administration:
- the transmission network management has become a separated entity within EDF, and is now named "Réseau de Transport Electrique" (RTE).
- Voltage quality is a more and more demanded criterion, especially by customers like Internet Service Providers and factories with production lines. Busbar coupling improves the voltage quality by increasing the Short-Circuit Power (SCP), but leads to very high current in case of short-circuit.

A limiter could solve this problem (Figure C 2: Config. A).

The deregulation permits to new Independent Power Producers (IPP) to connect to the grid. This contributes to increase the SCP and the voltage quality, but it raises new problems in case of short-circuits (Figure C 2: Config. B).

Insertion of FCL can avoid the replacement of existing equipment when the power consumption increases (Figure C 2: Config. C), especially in urban environment.

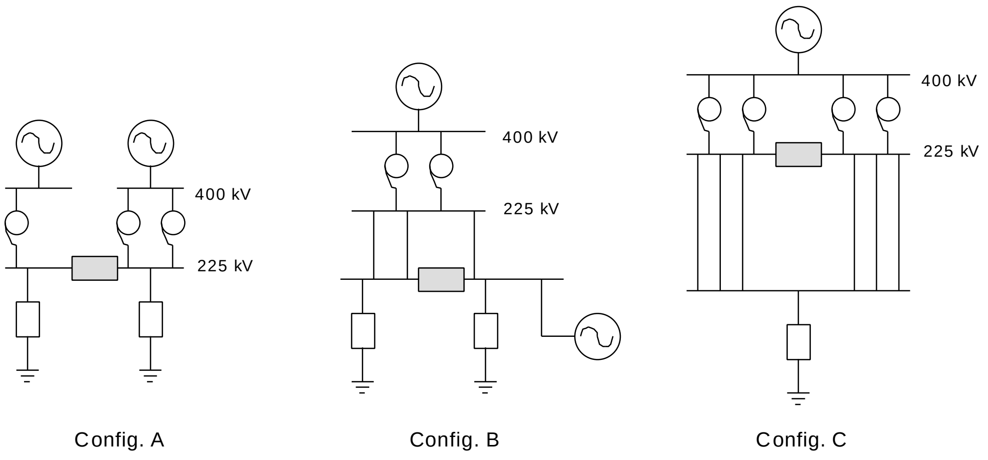

Figure C 2: Several configurations for a limiter insertion.

Today's solution to avoid damages on the equipment in case of short-circuit consists in their over-dimensioning, that is an expensive solution; one limiter could protect several devices having a rating power adapted to the real use.

Power-plant connections: a limiter in series with the main transformer could permit to reduce its reactance and the resistive losses, and thus to improve the voltage quality. In case of short-circuit outside the power plant, the transformer and the alternator would be protected. However, since the limiter is placed downstream regarding the alternator, it is not possible to reduce the dimensioning of the alternator; the main gain concerns the transformer and the circuit breaker (a 60kA device could be replaced by a 40 kA one, saving around 100 kEUR).

5.3 Utility C: RWE Net - Germany

5.3.1 Introducing RWE Net

RWE Net operates a 380 kV and 220 kV transmission system, a 110 kV sub-transmission system and a distribution system at different voltage levels between 5 kV and 30 kV, but mainly at 10 kV and 20 kV. The system length and the number of bays are given in Table C 4.

nominal voltage [kV]	380	220	110	5.5 ... 35
circuit length [km]	5081	6.822	13709	~ 53000
bays	325	798	3.985	~ 100000

Table C 4

Short circuit currents and system layout:

The maximum short circuit current are presented in Table C 5. Due to the high degree of system meshing rather high short circuit currents may occur in certain areas. Therefore short circuit currents of 80 kA in 380 kV and 63 kA in 220 kV which are abnormal in Europe had to be taken into account for system layout. In 110 kV the max. short circuit can be limited to 31.5 kA, since the 110 kV system is subdivided in different sub-grids.

Up to now the short circuit currents could be governed by a corresponding system layout, an adequate substation design and by installation of passable switching equipment. But studies and investigations have shown that advantages can be obtained by application of fault current limiters with regard to system layout.

nominal voltage [kV]	380	220	110	5.5 ... 35
short-circuit current [kA]	63 (80)	50 (63)	25 (31,5)	12.5 ... 20 (25)

Table C 5

5.3.2 Benefits of SFCLs with regard to system layout

In particular the super-conducting technology and with this SFCLs combine features for switching equipment which in sum cannot provided by conventional devices. The benefits of SFCLs have to be considered with regard to the system layout and not only related to the equipment itself. This aspect should be discussed in the following by means of different examples.

The first example (Figure C 3) presents a medium voltage substation fed from the 110 kV grid in which the bus-bars are coupled via a SFCL and additionally low impedance transformers in series with SFCLs are used. Today the short-circuit voltage of the transformers is designed so that the short-circuit power of the MV station is limited to 250 MVA.

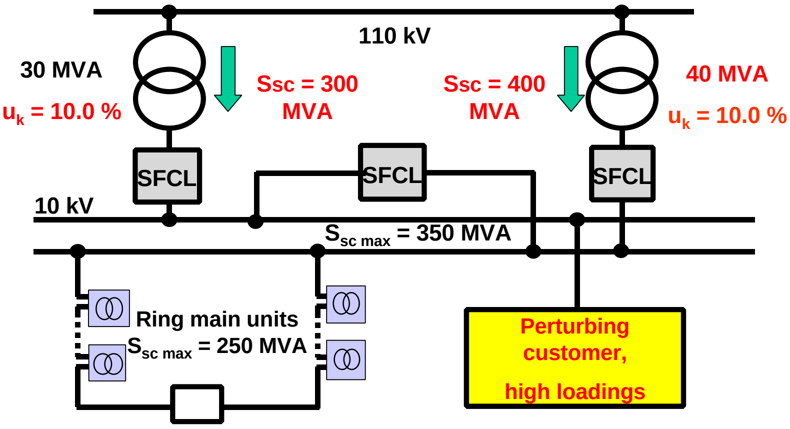

Figure C 3: MV busbars coupled via SFCL and low impedance transformer in series with SFCL

The admissible short-circuit capability of the station indeed is 350 MVA, but different ring main units of 250 MVA short-circuit capability connected to the MV bus-bar require a limitation to 250 MVA. Furthermore, the station is operated with two separate bus-bars. The most economical short-circuit-voltage of the transformers would be 10 %. In consequence the short-circuit power will increase to 300 MVA and 400 MVA respectively. By application of SFCLs in the transformer feeders the admissible short-circuit capability can be obtained.

A further improvement is to be achieved by bus coupling feeder installed with a SFCL In this way the short-circuit power of the station is increased nearly three times from 250 MVA to 700 MVA in total. By this means also voltage-disturbing customers and high loadings can be connected directly to the MV station and the connection to the higher voltage level can be avoided.

Compared to the investment costs for a connection to higher voltages level, the 110 kV grid e.g., the installation of the SFCLs in the way suggested will be an economical solution, reasonable costs for the SFCL presumed.

A similar situation exists regarding the connection of distributed generation and wind turbines to the MV grid. Here it becomes more and more difficult to connect such generators to the grid without a device limiting the short circuit current of the generator. In some MV stations the limits are already reached by the contribution of the feeding 110/10 kV transformer and no more margin is left for additional short-circuit currents coming from distributed generation. Therefore nowadays these generators have to be connected to the 110 kV grid via an expensive generator transformer. By means of a SFCL those generators could be connected to the MV grid.

The second example (Figure C 4) is related to coupling of 110 kV sub-grids. The 110 kV system is subdivided into different sub-grids to cope with a rated short-circuit current of 31.5 kA. With regard to the transformer capacity feeding into the 110 kV sub-grid the (n-1)-criterion has to be fulfilled and an outage of one transformer to be taken into account.

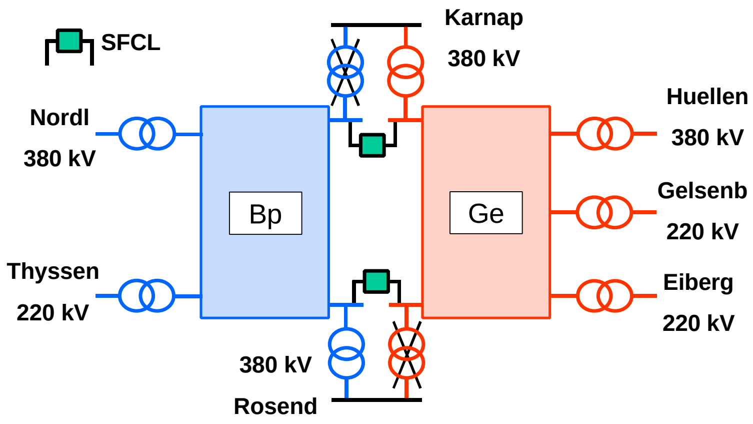

Figure C 4: Two 110 kV sub-grids coupled via SFCL

The surplus of transformer capacity can considerably be reduced by coupling two 110 kV sub-grids and by installing SFCLs into the bus coupler bay of the two 110 kV stations in question. In case of a transformer outage in one sub-grid the other sub-grid is able to deliver the reserve power and in case of a short-circuit the SFCL limits the short-circuit current to admissible values.

The cost savings for two 380/110 kV transformer feeders are in the range of 10 million Euro. Under the premises of a cost relation between a conventional 110 kV circuit breaker and a 110 kV SFCL of 1 to 10 a very economical solution may be achieved by the before mentioned installation.

5.4 Utility D: EnBW - Germany

5.4.1 Introducing EnBW

EnBW produces 10 % of the German electricity (3th utility in Germany) with nearly 78 TWh in 2000. It has many investments in Central Europe, Hungry, Check Rep., Switzerland.

The maximal admitted short-circuit current at 20 kV is 14.4 kA. The opening time is 0.1 s.

5.4.2 EnBW's project in Fault Current Limitation

EnBW is involved in two projects. Both concern Superconducting Fault Current Limiters.

The first one consist in the development of a 20kV Superconducting FCL in the framework of a German-Israeli partnership. The second project is sponsored by the German Ministry for Research and Technology (BMFT). Its goal is to develop a demonstrator aimed to be tested in the grid. All partners are German.

In a study dated from 1997, EnBW identified like potentially interesting the following configurations:

- protection of the old equipment and lines in the 20kV grid, alternative to reinforcement works of the grid equipment
- protection of weak parts of a substation, and bus bar coupling
- protection of the weak parts of the 20kV-grid after installation of a new transformer of increased rated power
- people safety and earth fault current limitation..

5.5 Utility E: The National Grid Company - England and Wales

5.5.1 Introducing National Grid Company

National Grid is the network operator in England and Wales and owns and operates the high voltage 275 kV and 400 kV electricity transmission system and provides services to a variety of customers e.g. generators, interconnectors, distributors and suppliers.

The national peak demand and annual energy supplied by the transmission system are about 51 GW and 300 TWh respectively.

The basic system characteristics are summarized in the table below :

System Voltage	AC Overhead Circuit Length (km)	AC Underground Circuit Length (km)	DC Underground Circuit Length (km)
400 kV	10052	132	
275 kV	3615	425	
±270 kV			327

Table C 6

5.5.2 Past experience

The separation of generation and transmission in England and Wales took place in 1990. This gave rise to great uncertainty in the future location, size and timing of openings and closures of generation plant. Since 1990, we have connected about 25 GW of generation plant to the transmission system and accommodated the closure of similar amount. There are already several power importing and exporting areas on the transmission system and some of the latter having very large concentrations of generation plant.

No. of Transformers	721
No. of Substations	325
No. of Towers	21800

Table C 7

National Grid currently utilizes current limiting series reactors connected in an inter-bus arrangement at 400 kV and 275 kV substations. More information is given in the table below:

No. of Series Reactors	Connection Voltage	MVA Continuous Rating
4	400 kV	1320 1860 2000 2640
4	275 kV	530 3 x 750

Table C 8

5.5.3 Current and future needs

The disadvantages of splitting the network to reduce fault levels, or introducing series reactors in terms of the effect on network steady state and transient performance are well known.

When fault levels exceed equipment ratings, the option of replacing switchgear and/or up-rating substation infrastructure can be expensive. There is a need for cost-effective new generation fault current limiters for connection at 400 kV on the National Grid transmission system.

Besides the general specifications on impedance, rating, etc, the limiter speed of response must be sufficient to limit the short-circuit making current and hence it should operate within a few milliseconds. Also, the limiter must be capable of recovering and of “seeing” another duty due to the possibility of delayed auto-reclosure of transmission circuits on a persistent fault.

5.6 Utility F: Manitoba Hydro - Canada

5.6.1 Introducing Manitoba Hydro

Manitoba Hydro is a major energy utility headquartered in Winnipeg (Province of Manitoba, Canada). It has over 5000 MW of hydroelectric generating capacity, mainly produced by the 12 hydroelectric generating stations. It also is the province's major distributor of natural gas, purchasing over 80 per cent of its supplies from Alberta producers.

Manitoba Hydro's transmission system transports electricity in a range from 24 kV to 500 kV. The major high voltage transmission lines operate at 115 kV, 138 kV, 230 kV and 500 kV. At the terminal stations located near major use centres, large transformers reduce the voltages to 66 kV, 33 kV or 24 kV. Voltage frequency is 60 Hz. Over 18500 kilometres of transmission lines, 33 kV to 500 kV, transport electricity throughout the province.

5.6.2 Manitoba Hydro's experience in Fault Current Limitation

Manitoba Hydro's experience to date has been limited to one outdoor device. A trial device on the 24 kV system has been installed in 1991. The device was a pyrotechnical limiter made in the US and was rated 27 kV, 2500 A. It was installed in a bus tie position to limit the short circuit current seen by the feeder breakers. At the time this was the only device on the market suitable for outdoor installation. The trial device has been installed as it offered a very economical "fix" for our underrated feeder breakers.

However, the operating experience has not been very good. In 1995 it failed catastrophically due to a faulty isolation transformer. The manufacturer replaced the unit with a redesigned version. In 1998 an unexplained operation of one of the phases occurred. C phase fired during 24 kV switching causing an unbalance because only two phases were carrying load through the bank tie breaker. The neutral overcurrent relay tripped the bank. Although the investigation could not find the reason for the FCL firing it is suspected that operating the capacitor bank is what triggered the event.

5.6.3 Manitoba Hydro's forecast in protection device

Because of this experience, Manitoba Hydro has been hesitant to install any more on its system, even though it has many locations where a FCL could be used to help defer circuit breaker replacements. Manitoba Hydro's opinion is that the development of an industry specification for short circuit current limiters would go a long way towards addressing its concerns about the reliability of these devices.

5.7 Utility G: Hydro Québec - Canada

5.7.1 Introducing Hydro Québec

Hydro Québec is the major utility in the Province of Québec with a power capacity of 36800 MW (more than 90 % from hydroelectricity).
The high voltage levels are 735 kV, 315 kV, 230 kV, 120 kV. Since the catastrophe of 1998 storm, grid reinforcement is considered as a priority.

5.7.2 Hydro Québec experience in FCL

The following applications were considered:

- use of a FCL in new power at 13.8 kV in order to reduce the fault current at the 330 kV substation where the power will be integrated.
  Reference case: Toulnustouc Power station. Without FCL, the integration of this new power station on the 330 kV network will require the replacement of some circuit breakers at 330 kV (because the fault current level is higher than the capabilities of the existing CB).
- Use of a FCL on the "regional meshed networks" at voltage levels up to 330 kV to avoid to split to main bus bars in the substations.
- Use of a FCL for 735 kV series-compensated lines in order to reduce the energy constraints on varistors. Savings on the varistors.

5.8 Utility H: Con Edison - USA

5.8.1 Introducing Con Edison

Consolidated Edison is a regulated utility providing energy (gas and electricity) in the region of New-York City and Westchester County. Its electrical generation capacity is almost 8500 MW. The system features almost 90000 miles (145000 km) of underground cable. And 35000 miles (56300 km) of overhead electric wires complement the underground system.

Presently, all circuit breakers at Con Edison’s bulk power transmission substations are operated within their interrupting capabilities. However, during the next few years, developers have proposed plans for the interconnection of approximately 8200 MW of new generation projects to the Con Edison transmission system. The interconnection of these projects would increase the magnitude of fault currents to levels significantly above the ratings of the breakers at various 345 kV, 138 kV and 69 kV substations. Fault current levels would increase to approximately 71 kA on the 345 kV system and to approximately 83 kA on the 138 kV system, thereby, exceeding the highest rated breakers (e.g., 63 kA) on the Con Edison transmission system.

Implementation of the Fault Current Management Plan will provide adequate fault current mitigation to permit all the proposed generating facilities to safely interconnect to the Con Edison system. This will help promote the expansion of an independent generation market in New York State.

5.8.2 Con Edison experience in FCL, management plan description

The proposed interconnection of new generating units to the Con Edison transmission system would result in fault currents that exceed the interrupting capability of existing circuit breakers at various Con Edison Bulk Power Substations.

For the purpose of mitigating these fault currents to acceptable levels, a fault current management plan (the Plan) has been developed. The Plan consists of the following system upgrades:

- installing a series reactor in each of four 345 kV feeders connecting the north and south end of the system
- installing a series reactor in a138 kV feeder connecting two substations
- installing a bus tie series reactor at a 138 kV switching substation
- installing a bus tie Phase Angle Regulator at a 138 kV switching substation
- moving the interconnection point of two 138/13.8/13.8 kV area substation transformers to another switching substation
- replacing two 345 kV, thirty-eight 138 kV and twelve 69 kV circuit breakers.

All study work was performed in accordance with the NPCC Basic Criteria, the NYSRC Reliability Rules, and the Con Edison System Transmission Design and Operating Criteria. The study conclusions are as follows:

Fault Duty Analysis:

The Plan will permit the interconnection of approximately 8200 MW of new generation to the Con Edison system (of which approximately 5500 MW are located in-City) by keeping fault current levels below the rated interrupting capability of circuit breakers at all 345 kV, 138 kV, and 69 kV Con Edison transmission substations.

Thermal and Voltage Analysis:

Power flows for normal system conditions can be controlled within applicable ratings through normal operating procedures (this may result in some bottled up generating capacity in the In-City load pocket). Power flows on all transmission feeders are also within applicable circuit ratings following first and second contingency conditions. The same can be said about the voltage performance at all transmission substations.

5.9 Utility I: KEPCO - Korea

5.9.1 Introducing KEPCO

KEPCO (Korea Electric Power Company) is the national utility in Korea since 1961; it is today also involved in overseas projects in Philippines and China. In 2001, Government-led restructuring is under way to introduce competition into the Korean electric power industry. In the first stage of restructuring, KEPCO's power generation sector was transferred to six newly-established power generating subsidiaries.

KEPCO power generating capacity was 51 GW and 285 TWh in 2001. The major transmission system voltages in KEPCO are 154 kV, 345 kV and 765 kV at present. The construction of some part of 765 kV transmission line and substation was finished and KEPCO started the commercial operation of 765 kV transmission system in 2002.

The main distribution system voltage of KEPCO is 22.9 kV. Large customers are adopting 3.3 kV, 6.6 kV or 22.9 kV as their distribution voltages.

5.9.2 KEPCO experience in FCL

Distribution system in KEPCO
22.9 kV: So far there has been no serious problem with high fault currents. The maximum breaking current rating is 25 kA. Basically the impedance of 154 kV/22.9 kV power transformer is large enough to suppress the fault current to a reasonable level.
A more serious problem occurs from the side of electricity supply. The demand of electricity is still gradually increasing in Korea, especially in the region of large cities. However it's very difficult to get the spaces to expand or build new substations due to very expensive land price or shortage of land. It's expected that increasing the capacity of main transformers by 30 % can be possible by adopting the so-called hybrid type transformer technology. The real problem is that, even though KEPCO can get more capacity to supply for customers, KEPCO can't expand the feeders as many as required due to the fear of large-scale black-out when a fault occurs in one of the feeders. At present KEPCO is limiting the maximum number of feeders to 5-7. KEPCO thinks that superconducting FCLs could be a good solution for the above case.

Large customers
3.3 kV/6.6 kV/22.9 kV: Sometimes the fault current levels in some large manufacturers are expected to exceed the rated breaking current mainly due to the expansion of facilities.
Countermeasures: They have usually adopted higher ratings of circuit breakers or GIS in case of increased fault current levels. The Is-limiters have also been adopted by a few customers. At present the maximum rating for 22.9 kV system is 40 kA, and for 3.3 kV/6.6 kV is 50 kA. It is expected that more efficient equipment like superconducting FCL could be introduced to the cases of increased fault current levels in near future.

Transmission system in KEPCO
154 kV/345 kV: The increase of fault current level is a serious problem for KEPCO. The following tables show the situation of fault current level of KEPCO.

Year	Total number of substation	Number of substation where the fault current exceeds		
		31.5 kA	50 kA	Total
1998	439	21	62	83
1999	449	33	81	114
2000	467	37	94	131

Table C 9: Situation of fault current level in 154 kV system

Countermeasures for 154 kV system:
- the CBs or GISs where the fault current exceeds the rated breaking current have been replaced with those of higher breaking ratings (e.g. 50 kA).
- The function of bus tie or bus coupling has been removed at the locations where the fault current exceeds the rated breaking current.
- CLR (Current Limiting Reactor) has been adopted in the neutral ground line of the 2nd side of 154kV/22.9 kV main transformers to reduce the fault current of single line to ground fault.

Year	Total number of substation	Number of substation where the fault current exceeds 40 kA
1998	55	8
1999	56	9
2000	61	14

Table C 10 : Situation of fault current level in 345 kV system

Countermeasures for 345 kV system:

- the CBs or GISs where the fault current exceeds the rated breaking current have been replaced with those of higher breaking ratings (e.g. 63 kA).
- The function of bus tie or bus coupling has been removed at the locations where the fault current exceeds the rated breaking current.

5.10 Other experience: Japan

5.10.1 Power system in Japan

There are 10 electric power companies in Japan, which are doing generation, transmission and distribution. Total amount of the power capacity is about 230 GW. IPP business has been started recently due to deregulation, but the power capacity is not so big so far.

Ratings of typical power system are as follows:

Rated voltage [kV]	Rated short circuit current [kA]	Rated current [A]
3.6	16 – 40	600 – 3000
7.2	12.5 – 63	600 – 3000
12	25 – 50	600 – 3000
24	12.5 – 63	600 – 4000
36	12.5 – 40	600 – 3000
72	20 – 40	800 – 4000
84	20 – 31.5	800 – 4000
120	25 – 40	1200 – 6000
168	25 – 40	1200 – 6000
204	25 – 50	1200 – 6000
240	31.5 – 63	2000 – 8000
300	31.5 – 63	1200 – 8000
550	50 – 63	2000 - 8000

Table C 11

5.10.2 Experience in Fault Current Limitation

Fault Current Limiter (FCL) is not used in Japan commercially so far. Short circuit current capacity is controlled by system construction planing, bus tie separation and high impedance transformer. In some case HVDC, FC and BTB are used for preventing enlarging short circuit capacity, which are mainly for adaptable power flow control.

FCL technologies have been studied in universities, electric power companies and manufactures. The major results are, for example, 6.6 kV, 1 kA superconductivity resistor type FCL (Tokyo Electric Power – Toshiba), 7.2 kV, 600 A thyristor and diode bridge type FCL (Nisshin Denki) and 7.2 kV, 400 A driven arc type FCL (CRIEPI – Tohoku Electric Power –Sankosha). The last one had been tested on the field for 2 years and 4 months. 22 kV or 66 kV applications are being studied and developed recently.

In future localized power generation plant or widely installed IPP may cause short circuit capacity problem. The FCL technologies can have the potential as one solution of the problem.

Part D

Fault Current Limiters - Testing

D Fault Current Limiters - Testing

1. Introduction

The operation of fault current limiters (FCL) differ completely from normal current breaking devices that operate at natural current zero. Nevertheless FCLs will be used in applications nearby or even integrated in existing switchgear.

Up to now there is no international standard available for FCLs. Appropriate testing methods to test the characteristics of FCLs should be discussed and included into the standards.

So long a standard for FCLs is not available, from a type test point of view, FCLs have to be compatible with existing standards as IEC taking into account the exceptional characteristics of the devices.

2. Dielectric test

For dielectric tests AC withstand voltages and lightning impulse withstand voltages have to be considered according to international standards. These tests have to be performed in closed position between the phases and between the phases to ground according to the requirements of insulation co-ordination (IEC Publication 60071-1) and the common specifications for high-voltage switchgear and controlgear standards of (IEC 60694). According to the scope of this working group the highest voltage for the FCL is up to 145 kV.

Highest voltage for equipment U_m (r.m.s. value)	Standard short-duration power-frequency withstand voltage (r.m.s. value)	Standard lightning impulse withstand voltage (peak value)
7,2 kV	20 kV	40 / 60 kV
12 kV	28 kV	60 / 75 / 95 kV
17,5 kV	38 kV	75 / 95 kV
24 kV	50 kV	95 / 125 / 145 kV
36 kV	70 kV	145 / 170 kV
52 kV	95 kV	250 kV
72,5 kV	140 kV	325 kV
100 kV	150 / 185 kV *)	380 / 450 kV
123 kV	185 / 230 kV *)	450 / 550 kV
145 kV	230 / 275 kV *)	550 / 650 kV

*) The higher levels are applicable in case of phase opposition

Table D 1

The insulation performance of the “open” FLC or the combination of a FCL and a switch has to be proven also, whatever the open configuration is (semi-conductor device or gap of an auxiliary switch or circuit breaker). The test requirements should be adapted to the actual conditions of an open circuit breaker between two parts of a grid, eventually including phase opposition. Additionally the long term performance should be considered especially in the case of semi-conductor devices.

3. Temperature-rise test

These tests shall be made with a three-phase device including the enclosure at nominal three-phase current. Temperature rise of contacts and the relevant parts should be within the specifications of IEC. The temperature rise of non accessible parts as, for example, contacts in vacuum interrupters, silicon wafers in semiconductor devices or of superconducting materials may deviate from above mentioned specifications. The measurement of resistance of the main current path should show values within the acceptable limits according to IEC.

Temperature-rise test at a continuous current at a power frequency (50 / 60 Hz).
Measuring of the resistance of the main current path
IEC-Publication 60694, 2001-5
IEC-Publication 60298, 1990-12
IEC-Publication 62271-100, 2001-5

4. Short-time withstand current test

This test for switching devices, busbars and FCL has to certify the electro-dynamic and thermal capability of the system. The connection of the FCL at the supply side, or in case of a bus tie at both sides, should be made strong enough to withstand the asymmetrical peak and the rated short circuit current for 1 or 3 seconds. This should be proven using a bolted short circuit test (IEC 60694). The short circuit test plant can have reduced voltage capability, in order to deliver the correct prospective current.

FCL (Self triggered)	**FCL (External triggered)**	
Type A: In case of self triggered FCL the prospective short circuit current shall be applied to the FCL, but the device has not to withstand this test current, because the self triggered FCL is limiting the fault current in the first current rise before reaching the peak. (e.g. Superconducting FCL) For this device the active part has to be bridged or bolted on one or both sides and this should be proved by a short circuit test (IEC 60298).	***Type B:*** FCL device which is able to withstand the prospective short circuit current of the system (Pyrotechnical FCL or Hybrid FCL with a parallel contact). These devices should be tested with the prospective short circuit current without limiting operation (IEC 62271-100) The trigger device must be deactivated.	***Type C:*** FCL device which is not able to withstand the prospective short circuit current (e.g. Semiconductor FCL without a parallel contact). The test can only be made with bridged or bolted connections as for Type A.

Table D 2

5. Breaking/making tests

For this test no existing standard document is available, so new rules have to be defined. The tests shall verify the limiting parameters of the device in question. Tests have to be made at maximum system voltage in a three-phase circuit (only for device up to 36 kV). The short circuit impedance of the source should be so low that the prospective (unlimited) short circuit current would flow in case the FCL would not operate. Test at different making angles are to be recommended, for example a symmetrical test making at maximum voltage between two phases and an asymmetrical test making at zero voltage between two phases. The third phase can be made at the same instant. Records of the limited short circuit current and the recovery voltages afterwards should be made with appropriate equipment as usual for switching tests with circuit breakers. The test circuit of the FCL has to be defined to cover the TRV-standards resulting on the applications.

When FCL has not only an opening function but also a closing function, the making test can be combined with the breaking test described before.

Breaking test of FCL have to be made in full rated high power laboratories in a direct test circuit with the three-phase rated voltage and current (only for device up to 36 kV).

- Breaking test with a current (rated frequency / cosφ <= 0,15) just below the minimum tripping value
- Breaking test with a current (rated frequency / cosφ <= 0,15) just above the minimum tripping value
- Breaking test with the maximum breaking current (rated frequency / cosφ <= 0,15)

6. Endurance test

Depending on the FCL-technology the endurance test has to be done with an appropriate number of operations and procedures.

7. EMC – test

EMC-Tests are today required only for secondary systems with electronics (Burst-Test and Oscillating Waves). Is a FCL sensible against such applications? If “yes” an essential question is the amplitude of the test requirements.

- Burst – test (against fast transients)
  IEC publication 61000-4-4

- Electrostatic discharge (ESD)
  IEC publication 61000-4-2

- Electromagnetic Field Strength, Emission of electromagnetic waves
  EN 50081 Part 2

- Electromagnetic Susceptibility (EMS)
  EN 61000-4-3

For a safe operation of FCL device it is advisable to check the EMC.

Part E

Literature

E Literature

This part E contains an extensive literature list regarding the subject of fault current limiting in general. The list was matched by the WG members during the work on part B, C and D of this Technical Brochure and is related to these parts as well.

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