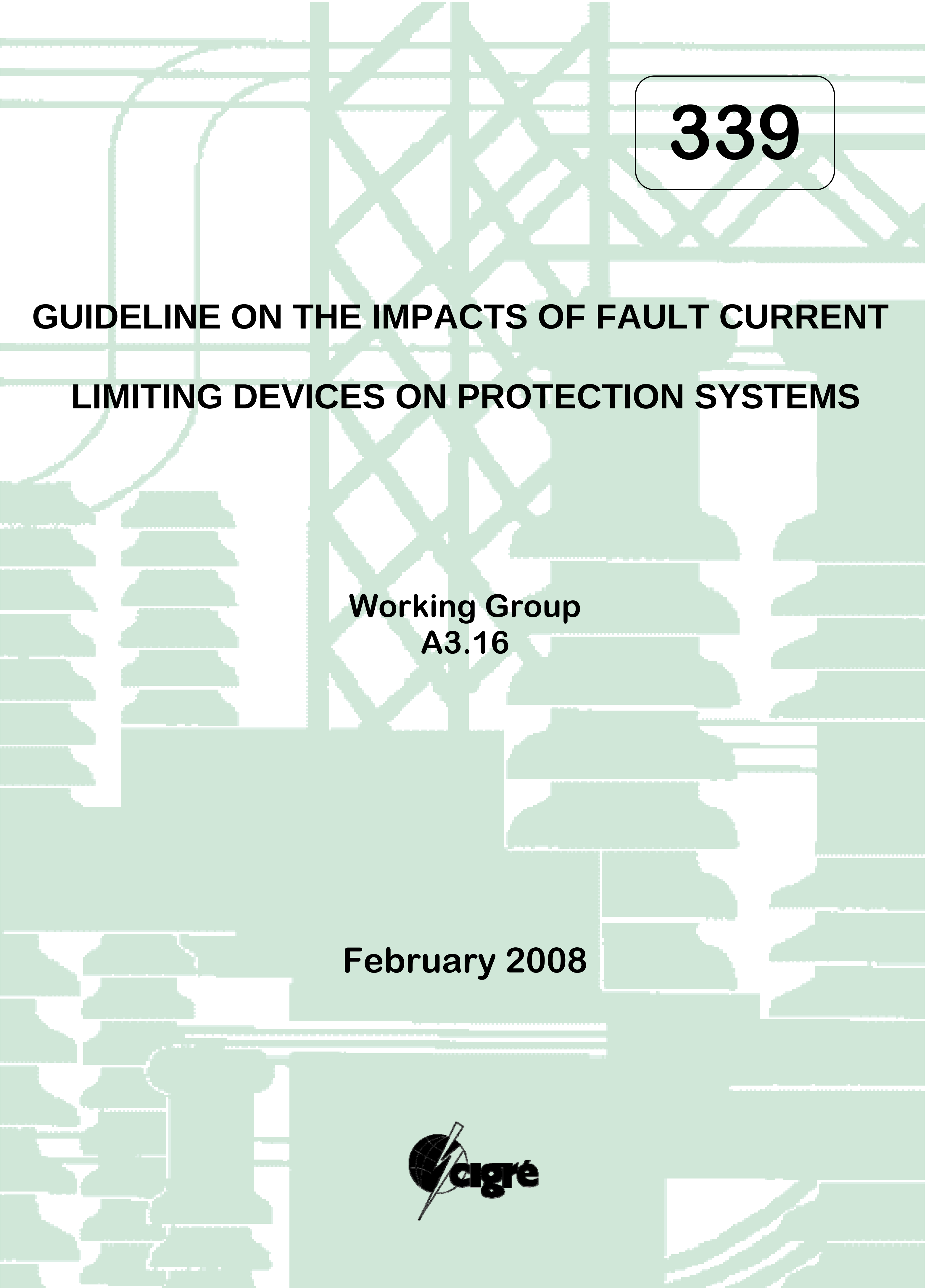

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GUIDELINE ON THE IMPACTS OF FAULT CURRENT LIMITING DEVICES ON PROTECTION SYSTEMS

Working Group
A3.16

February 2008

WG A3.16

Guideline on the impacts of fault current limiting devices on protection systems

February 2008

Members of A3.16:

H. Schmitt - DE (Convener)

J. Amon Filho - BR; D. Braun - CH; G. Damstra - NL; K.H. Hartung - DE

N. Higuchi - JP ; J. Jäger - DE; J. Kida - JP; L. Martini - IT

M. Steurer - US; C. Umbricht - CH; X. Waymel - FR

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ISBN 978-2-85873-027-8

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Foreword

CIGRE Working Group (WG A3.10) concluded its work by publishing the CIGRE Technical Brochure No. 239 entitled "Fault Current Limiters in Electrical Medium and High Voltage Systems" [1]. A new CIGRE Working Group A3.16, established in 2003, continued the work by focusing, in a first step, on the interaction between different fault current limiting technologies and existing protection concepts in medium voltage (MV) or high voltage (HV) systems.

A questionnaire was sent out by the WG A3.16 in 2003 asking utilities for typical structures of distribution systems, type of protection used in their networks, as well as for their needs regarding limitation of short circuit currents in MV and HV networks. Based on the of 53 responses received from 14 different countries it was found that mostly electromechanical relays are installed in today's electrical systems. In future, electronic or digital protection equipment will likely be installed in the case of new installations. The main protection principles used are distance, differential, and over-current protection. Compared to a previous survey carried out in 1996 the answers to the new questionnaire show an increase in the need for fault current limitation, especially in the HV level between 110 kV and 145 kV. The complete results of this inquiry are shown in APPENDIX A. Another study on utility needs and perspectives regarding fault current limiters (FCL), performed by EPRI in 2004, concluded with similar findings [2].

The introduction of FCLs has an impact on the protection schemes and functions in electrical systems. Depending on the current limiting technique used, today's protection concepts have to be adapted or revised to ensure proper network protection selectivity. A relationship between fault current limiters and protection schemes should be established by taking into account both protection and network specific issues, such as the impact of different FCL technologies, existing and new protection concepts, selectivity, and innovative network configurations.

In a first step, the WG focuses its investigations on the three main protection principles: overcurrent, distance, and differential protection. The different FCL techniques such as limiting reactors, superconducting FCLs, power electronic FCLs (e.g. solid state FCL breakers) or pyrotechnic FCLs (such as the I_s-limiter) are considered with their representing characteristic principles (black box) rather than with their real physical behavior.

The wide range of FCL applications possible may cause too many different interactions and influences between network and FCLs to be considered in a single study. Therefore, this Working Group focuses only on FCL applications installed in the distribution network at the bus-tie, at the outgoing feeder, and the incoming feeder.

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Glossary

ac - abbreviation for alternating current

active power - see real power

alternating current - an electrical current which reverses direction periodically due to a change in voltage which occurs at the same frequency. Often abbreviated AC or ac.

analog - a measuring or display methodology which uses continuously varying physical parameters. In contrast, digital represents information in binary form using only zeros and ones.

apparent power - the algebraic product of voltage and current in ac systems. Since voltage and current may not be in phase on ac systems, the apparent power thus generally does not equal the real power. Reactive loads (inductance and/or capacitance) on ac systems will cause the apparent power to be larger than the real power.

capacitor - a device that stores electrical charge, usually by means of conducting plates or foil separated by a thin insulating layer of dielectric material. The effectiveness of the device, or its capacitance, is measured in Farads (F).

circuit breaker - a device designed to open and close a circuit (make or break a current) either by manual action or by automatic action. As opposed to a regular switch, a circuit breaker is designed to interrupt fault currents. A circuit breaker can provide overcurrent protection when combined with a protection relay or trigger unit that commands the breaker to open when current exceeds a pre-set value.

conductor - usually a metallic substance capable of carrying electric current with little resistance. The best conductor at room temperature is gold, followed by silver and the most common conductor which is copper. Some other recently discovered substances called super conductors actually have zero resistance at extremely low temperatures (typically below 77 K, the liquefaction temperature of Nitrogen).

continuous load - a sustained electrical load current for three hours or more.

CT – abbreviation for current transformer.

current - the flow of electricity measured in amperes.

dc - abbreviation for direct current.

diode - an electronic semiconductor device consisting of an p-n-junction that allows current to flow in only one direction.

direct current - electrical current that flows in only one direction.

EHV – abbreviation for extra high voltage.

FACTS - abbreviation for flexible AC transmission systems.

fault – unintentional reduction of the phase-to-phase, phase-neutral, or phase-to-ground impedance, typically resulting the subsequent flow of a large current

FCL - abbreviation for fault current limiter.

feeder - circuit conductors between the service equipment and the last downstream branch circuit overcurrent protective device.

filter - a device made up of circuit elements designed to pass desirable frequencies and block all others. It typically consists of capacitors and inductors.

frequency - the number of complete alternations or cycles per second of an alternating current. It is measured in Hertz. The standard frequency in the US and many other countries is 60 Hz, while Europe and Asia (typically) maintains 50 Hz.

grid - in the electrical arena, a term used to refer to the electrical utility transmission and distribution network.

ground - a conducting connection between an electrical circuit or device and the earth. A ground may be intentional, such as in the case of a safety ground, or accidental which may result in faults and hence large overcurrents.

harmonic - a sinusoidal oscillation at an integral multiple of a base frequency. For example, the third harmonic on a 60 Hz system oscillates at a frequency of 180 Hz. Certain types of electrical equipment generate harmonics which interfere with the proper functioning of other devices connected to the same system.

HV – abbreviation for high voltage.

HVDC– abbreviation for high voltage direct current (transmission).

impedance - the total effect of an electrical circuit as it opposes the flow of current. In ac systems, the impedance consists of resistance (dissipating real power) and reactance (due to inductance and capacitance). Impedance is quantified in the units of ohms (Ω).

inductance - the proportionality between the rate of change of magnetic flux and induced voltage in an electric circuit. Typically, the change of magnetic flux is caused by the variation of the current in the circuit itself (self-inductance) or in a nearby circuit (mutual inductance). The inductance is measured in the units of Henries (H).

load - a device which consumes electrical power and is connected to a source of electricity.

MV – abbreviation for medium voltage.

neutral - a conductor of an electrical system which usually operates with minimal voltage to ground. In three phase systems it carries the unbalance of the phase currents. Systems that have one conductor grounded use the neutral for this purpose.

open circuit voltage - the maximum voltage produced by a power source with no load connected.

overcurrent - any current beyond the continuous rated current of the conductor or equipment. This may be a value slightly above the rating as in the case of an overload or may be far above the rating as in the case of a short circuit.

overload - operation of electrical equipment above its normal full-load rating or of a conductor above its rated capacity. An overload condition will eventually cause dangerous overheating and damage.

MHO-relay - distance protection relay utilizing a circular impedance characteristic which is representing the protection zone reach and the directional determination. The impedance characteristic is crossing the point of origin of the impedance plane.

power - the rate at which work is performed or that energy is transferred. Electric power is measured in watts (W). A power of 746 W is equivalent to one horsepower.

power factor - the ratio between real power and apparent power delivered in an ac electrical system (i.e. to a load). Its value is always in the range of 0.0 to 1.0 (or 0% to 100%). A unity power factor (1.0) indicates that the current is in phase with the voltage and that reactive power is zero.

protection number 21 - distance relay

A protection device that functions (trips) when the circuit impedance decreases beyond a predetermined value. It effectively measures the distance of the fault from the relay and hence can be used for selectivity between protection zones, typically on transmission systems.

protection number 50 - instantaneous overcurrent relay
A protection device that functions (trips) with no intentional time delay when the current exceeds a preset value.

protection number 51 - ac time overcurrent relay
A protection device that functions (trips) when the ac input current exceeds a predetermined value, and in which the trip current and operating time are inversely related throughout a substantial portion of the performance range.

protection number 67 - ac directional overcurrent relay
A protection device that functions (trips) at a desired value of ac overcurrent flowing in a predetermined direction.

protection number 87 - differential protective relay
A protection device that functions (trips) on a percentage, phase angle, or other quantitative difference of two or more currents (or other electrical quantity) across ist protection zone.

PT – abbreviation for potential transformer (also recognized as voltage transformer).

reactive power - the algebraic product of voltage and current consumed by reactive loads such as capacitors and inductors. These types of loads, when connected to an ac voltage source, will draw current which is quadratic to the voltage (i.e. 90^o out of phase) and hence they do not consume net real power over one cycle of the ac waveform.

real power - The term real power, also called active power, signifies the net power transferred within one cycle of the ac waveform. It is often used to qualify the general term power in order to differentiate from reactive power.

resistance - the characteristic of materials to oppose the flow of electricity in an electric circuit by dissipating real power. Resistance is quantified in the units of ohms (Ω).

rms or **RMS** - abbreviation for true "root-mean-square", a method of computing the effective value of a time-varying electrical signal. The basis is that the rms value of an ac quantity, applied in a dc circuit, dissipates the same amount of real power. For example, an ac current of one ampere rms produces the same amount of heat over one cycle in a given resistance as a dc current of one ampere in the same resistance.

RTDS – abbreviation for real time digital simulator, a registered trade mark of RTDS

Technologies in Winnipeg, Canada, a vendor of s real-time simulator system used to test power system protection relays.

SCFCL - abbreviation for superconducting fault current limiter

short circuit - a low resistance connection made between normally isolated points of an electrical circuit which may result in a large current flow, far above normal levels.

single phase - an ac electric system or load consisting of one pair of conductors energized by a single alternating voltage. This type of system is simpler than three-phase but has substantial disadvantages when large amounts of power have to be delivered.

SIR - abbreviation for source impedance ratio. SIR is the ratio between the source impedance and the fault impedance. The two impedances are bordered by the relay location. The higher the SIR the lower the voltage which is sensed at the relay location.

SSFCL - abbreviation for solid state fault current limiter.

surge capacity - the ability of an electrical supply to tolerate a momentary current surge or inrush imposed by the starting of motors or the energizing of transformers.

three-phase - an ac electric system or load consisting of three conductors energized by alternating voltages that are out of phase by one third of a cycle. This type of system has advantages over single-phase including the ability to deliver greater power using the same ampacity conductors and the fact that it provides a constant power throughout each cycle rather than a pulsating power, as in single-phase. Large power installations are three-phase.

thyristor - a solid-state semiconductor device with four layers of alternating N and P doped semiconductor material. A thyristor acts as a unidirectional switch, conducting when its gate receives a current pulse, and continuing to conduct as long as it is forward biased.

TRV - abbreviation for transient recovery voltage.

voltage drop - a voltage reduction due to impedances between the power source and the load. These impedances are due to wiring and transformers and are normally minimized to the extent possible.

1. Definitions

Fault current limiters (FCL) and protection systems go into action during fault conditions. Hence a joint investigation is necessary and useful. Different FCLs will influence the protection system in different manners, depending on the type of FCL, type of protection system, power system configuration, and type of interactions. The basic protection principles considered here are: overcurrent, distance, and differential protection. This may lead to a rather complex investigation due to the multiple possibilities of interactions. That is why a more narrow field of consideration will be defined first, followed by the basic FCL application methods, a review of the basic protection principle, and finally the framework established for this investigation.

1.1 Field of considerations

The questions to be answered by the present guideline should be:

- Which are the fundamental influences of FCLs on the basic protection principles depending on the FCL technology and FCL location?
- Can the existing protection system be maintained?
- If not, which difficulties have to be expected?

1.2 Basic FCL application methods

FCL applications are versatile. Two basic fields of applications of FCLs can be generally distinguished according to Figure 1 .

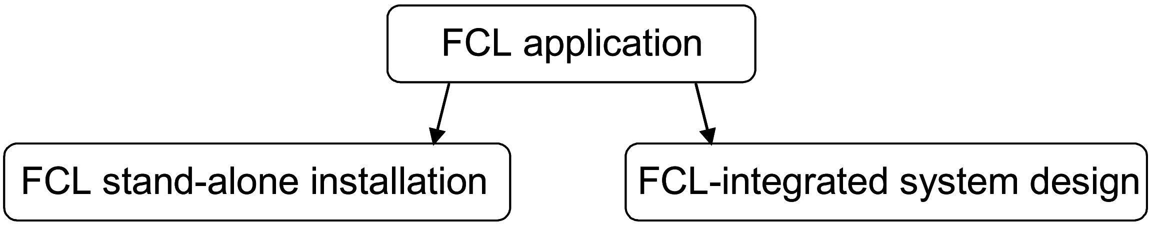

Figure 1 FCL application methods

The FCL application of a stand-alone installation in power systems is characterized by the following criteria:

- The FCL is applied to an existing or new substation which was designed with conventional fault current ratings

- The goal is to operate a substation with lower source impedances through the use of a FCL
- The FCL may be applicable to different locations within the switchyard
- The protection system (e.g. protection relays and instrument transformers) is only designed according to the existing substation or network configuration (i.e. prior to the introduction of an FCL)

Hence the FCL application of a stand-alone installation is typically representing the system condition arising from any extension or refurbishment activities that causes increased fault current levels which makes it necessary to consider the application of a FCL.

In contrast to the stand alone installation the FCL application of an integrated system design has the following characteristics:

- The FCL becomes an integral part of the substation design
- Hence, the substation design ratings are based on the limited fault currents caused by applying an FCL device
- The protection system is already adapted to fault conditions caused by the FCL
- Novel protection features like advanced pickup criteria or communication links are applied

Focusing this investigation to the stand-alone installation, which seems to be the more common one, allows for an elaborative analysis of the impacts of FCLs on the protection system to be accomplished with reasonable effort.

1.3 Basic protection principles

The following sections briefly describe the various protection principles and their fundamental sensitivities to FCLs.

1.3.1 Overcurrent protection (protection code number 50/51)

This protection principle is based on the analysis of the current value sensed by the current transformer (CT) to which the overcurrent protection relay is connected. The relay trips if the sensed current value exceeds the pickup setting value established to ensure proper trip for a fault occurring inside of the protection zone. One end of the protection zone is defined by the CT location (see section 1.3.7 for the definition of the protection zone). The monitored current value can be RMS, fundamental frequency, peak value, or any other characteristic current value. The relay can operate without any time delay (50) or considering a time delay (51) according to a constant or inverse current-time (“i” versus “t”) characteristic. As the overcurrent protection senses the current value of faults, any series connected device within the protected circuit, which affects the fault current magnitude, influences the operation and coordination of the overcurrent protection.

1.3.2 Distance protection (protection code number 21)

This protection principle is preferably used to protect sections of transmission lines. It operates based on the analysis of the downstream impedance seen by the relay, i.e. the quotient of the voltage and the current sensed by the respective PT and CT connected to the relay. One end of the protection zone is defined by the CT and PT location (see section 1.3.7 for the definition of the protection zone). In case of a fault, the relay measures the impedance of the faulted loop. Thus, the impedance of the line up to a certain length defines the other end of the protection zone. Once the impedance falls below that threshold the fault is considered to be inside this area. The distance protection relay will then trip, depending on the time delay involved in the protection coordination applied. For pickup an overcurrent or zone impedance pickup is most common.

The distance protection relay is measuring the impedance (or admittance) of the fault loop which for low impedance faults is proportional to the fault distance. This proportionality is not longer true in case an additional device is installed in series with the line impedance. Thus, in principle, the performance of the distance protection may be disturbed by introducing an FCL.

1.3.3 Directional protection (protection code number 67)

This protection principle is able to detect the direction of the current flowing. It operates based on a continuous comparison of the phase angle between the current and the voltage which are monitored by the CT and PT. The determination of direction is deduced from typical phase angle ranges to be expected on the protected line. If additional series devices are installed which influence the phase shift between current and voltage deviating from the expected value, the determination of current direction may fail. This protection principle is usually combined with either the distance protection or the overcurrent protection principle.

1.3.4 Differential protection - low impedance (protection code number 87-Low)

This protection principle is based on the vector sum of the currents flowing at the terminals of an electrical equipment, busbar, or even line (typically a short cable) to be protected. To cope with inaccuracies in the current measurements this function is restrained by the scalar values of these currents. The protection zone boundary is defined by the locations of the CTs (see section 1.3.7 for the definition of the protection zone). This protection principle is very selective. During a fault within the protection zone (internal fault) the vector sum and the scalar sum are nearly equal and the relay has a well defined criterion for tripping. During a fault outside of the protection zone (external fault), the vector sum approaches zero and the scalar sum corresponds to the through fault current, thus preventing the relay from tripping.

Saturation of a CT during external faults can lead to a large vector sum of currents causing the protection principle to trip unintended. Stabilizing measures and algorithms are then established to avoid this phenomenon. Two-end out-of-phase in-feed condition during faults inside the protection zone, which can be caused by an additional series device, produces a lower vector sum than under the in-phase condition. This can severely reduce the sensitivity of this protection method.

1.3.5 Differential protection - high impedance (protection code number 87-High)

This protection principle, just like the “87-Low” (see section 1.3.4), also utilizes the vector sum of the currents flowing at the terminals of an electrical equipment to be protected. However, unlike the “87-Low”, where the vector summation is either performed through an electromechanical relay arrangement or electronically through proper algorithms, here it must be realized by directly wiring high accuracy class CTs to the stabilizing resistor. The principle of this technique is that the “spill current” (current sum caused by CT saturation) passes through a saturated CT in preference to the stabilizing resistor. A restraining measure of the scalar sum (as in the “87-Low”) is not employed. Consequently, this method is less sensitive to CT saturation and out-of-phase in-feed conditions (i.e. as may be caused by FCLs) and thus exhibits higher sensitivities for fault detection while being less sensitive to effects caused by FCLs.

1.3.6 Protection system sub-items

Protection systems are comprised of the four sub-items described below.

Sensing: Transmission errors of transducers like CTs or PTs under steady state and transient conditions are causing a difference between the primary and the scaled secondary signals. Consequently, the protection relay is not sensing the primary quantity directly (i.e. it is not exactly sensing the "reality").

Pickup: The pickup unit distinguishes between load and fault conditions and is typically based on the current signal. If the current signals are not sufficient for a proper pickup, quantities like voltage or phase angles have to be used as additional criteria. Pickup includes the measurement, filtering and threshold process.

Processing: The measured values have to be evaluated regarding their magnitude, phase angle, etc. Based on that, the decision has to be made whether and when the corresponding circuit breaker must be tripped to clear the fault.

Coordination: For the realization of a selective, sensitive, and reliable protection system, the protection relays must be coordinated with each other. The coordination constraints are the actual network configuration, type of network devices, and the steady state and transient network behavior.

1.3.7 Protection zones

For a better classification of different interactions between FCLs and protection systems, the concept of protection zones is essential. It is a concept which is generally used for protection design and coordination. The focus of protection systems is to detect and to clear faults. This should be done preferably by each relay for any kind of fault type within its specification, but not for any kind of fault location. That means that faults which are defined to be cleared have to be located in dedicated areas assigned to the dedicated protection system. These areas are called "protection zones". Protection zones assigned to the primary protection systems, which means fault clearing as fast as possible, represent primary protection zones. Backup protection zones are areas overlapping with a primary zone, but assigned to another protection system as shown in Figure 2. Internal faults are located inside and external faults are located outside of the primary protection zone. In other words, faults in the primary zone should trip the protection with minimum delays, whereas external faults should not cause a primary trip, and for coordination purposes, may trip the protection with a specific delay.

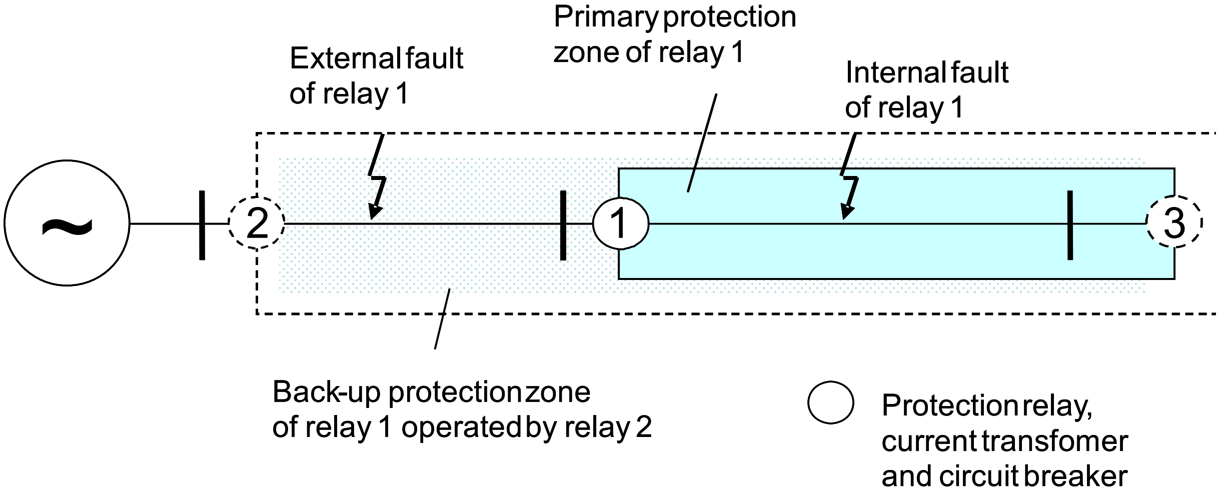

Figure 2 Protection zone concept: Primary and Backup protection zone

The protection zones are bounded precisely by the CTs to which the protection relays of the protection system is connected. In case of the protection zone of a differential protection, with at least two CTs under use, this is sufficient to be defined. In case of an overcurrent or a distance protection, one end of the protection zone is defined by the connected CT; the other end is defined by the set protection principles and settings, the in-feed conditions or the available network equipment. With this general approach the definition of a protection zone can be applied to a wide range of network configurations.

For example, the considered protection principle 50/51 of Figure 2 is non-directional. Thus, in principle *relay 1* is covering a bilateral primary protection zone. But because of the single-end feeding conditions, the primary protection zone is limited by *relay 1* at the left border. Fault locations between the in-feed and *relay 1* will not trip *relay 1*. The right border of the primary protection zone is given by the next downstream protection relay (*relay 3* in our example of Figure 2) and the respective circuit breaker.

The backup protection is covering the primary zone of *relay 1*, but it is operated by *relay 2*. If *relay 1* cannot clear the internal fault because of any reason, *relay 2* should do it as a backup system according to its specific parameter settings. The following investigations are based on this exemplified protection zone concept.

Due to the interactions between an FCL and protection systems one major classifying difference is whether the FCL is located inside or outside of the assigned protection zone. Figure 3 and Figure 4 illustrate these two sub-cases “FCL inside” and “FCL outside”, respectively.

Figure 3 shows the sub-case of protection zones applied to the protection principles 50/51, 21, and 87 where the FCL is located inside of the protection zone. For the protection principles 50/51 and 21 this sub-case could be ambiguous in some cases. The protection zone may include further downstream substations, e.g. if no relay is provided there. Thus, the FCL could also be located at one of the downstream line sections and the current flowing through the FCL is not equal to the current which is sensed by the relay. Figure 3a is representing the FCL location directly following the relay, Figure 3b shows the FCL location at the next line section. The protection zone of the function 87 is unique, regarding this matter, since it is two-side bounded by the current transformers of the protection system. In case of a multi-terminal differential protection system, the protection zone can also cover additional substations. Moreover, since the current will be measured at each terminal, the location of the FCL inside the protection zone, in principle, does not make any difference. However, the presence of the FCL device still may affect the sensitivity.

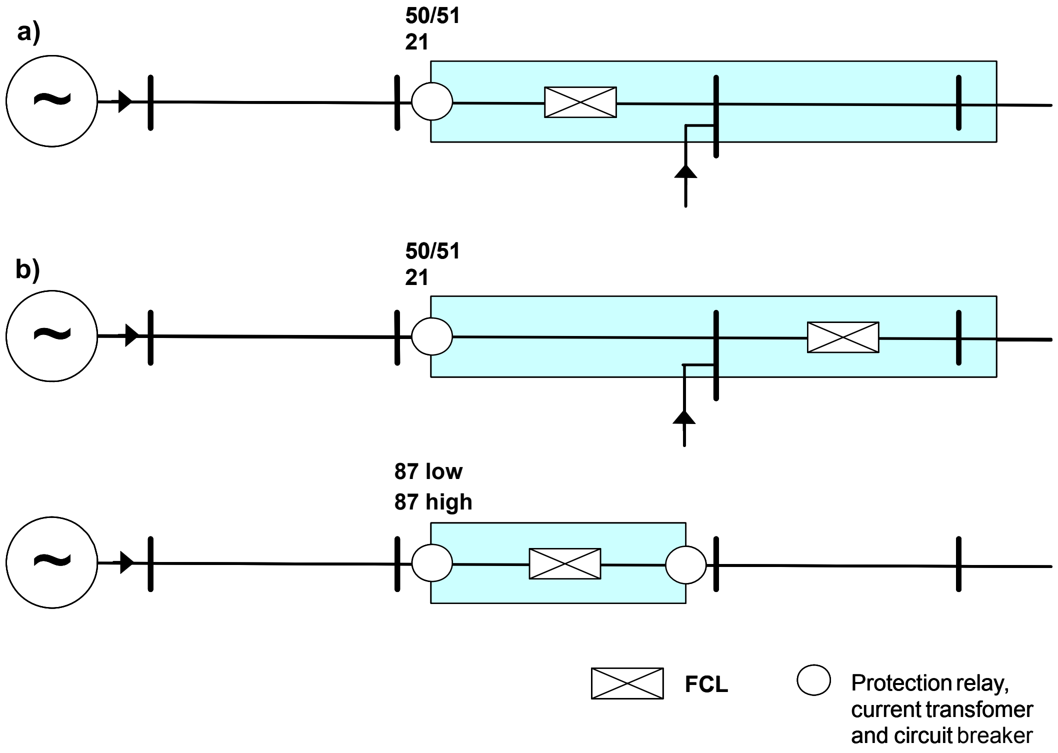

Figure 3 Schematics of protection zone concept and protection principles 50/51, 21 and 87 for the sub-case “FCL inside”

Figure 4 shows another set of cases of protection zones where the FCL is located outside of the protection zone. These cases are unambiguous for the protection principles 50/51 and 21 because the protection zone is not bounded on two sides. Further sub-cases have to be distinguished in the case of the function 87. Figure 4a and Figure 4b are illustrating this matter. The FCL can be located between the in-feeding source and the protection zone (see Figure 4a) or downstream of the protection zone (see Figure 4b). This results in two different fault current conditions during external faults. The protection principle 87 is particularly affected by the fault current during external faults. The higher the amplitude and the DC-component of the fault current during external faults the more the protection is endangered to malfunction. Therefore, lower fault current amplitudes and, depending on the X/R ratio of the FCL, lower DC-components can be expected.

Regarding the protection principles 21 and 67, the connection of the PTs to the network is considered at the same location as the CTs. By locating the PT downstream of any series connected device such as a FCL avoids the influencing problem in only one direction. The reverse direction is still impacted. Thus the different choice of the PT location does not solve all the problems. In this study the different PT locations are considered with the cases “FCL outside” and “FCL inside” according to Figure 3 and Figure 4 . Thus the PT location is of no further concern in this report.

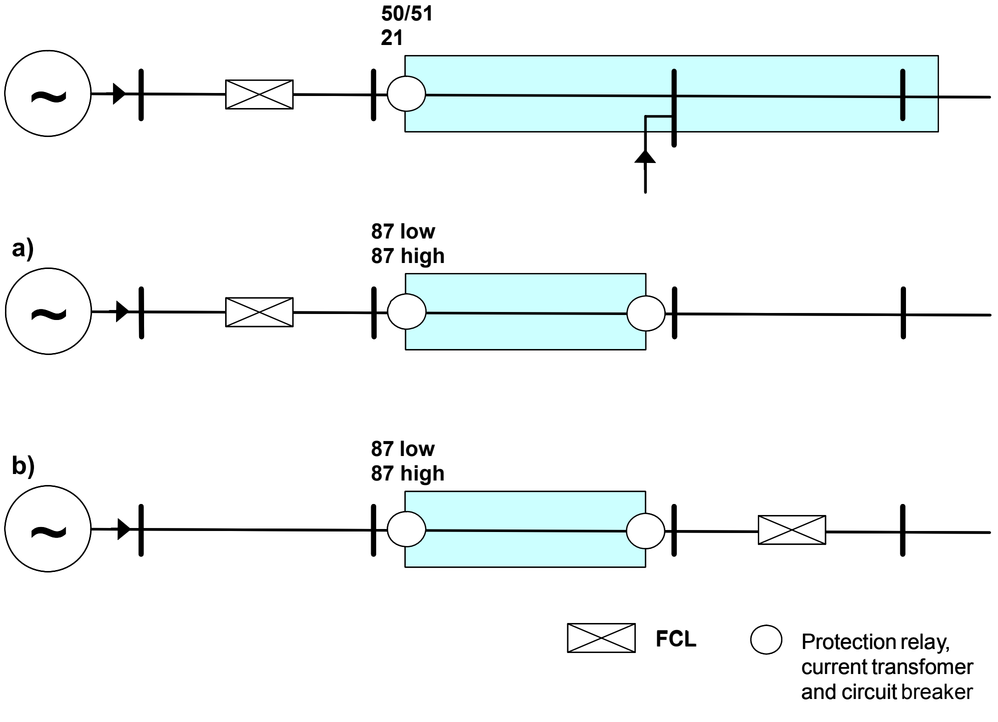

Figure 4 Schematics of protection zone concept and protection principles 50/51, 21 and 87 for the sub-case “FCL outside”

The presented protection concepts are not limited to the simplified configurations of Figure 3 and Figure 4. They are designed to be extended to all common network configurations if necessary. Nevertheless, the further discussions about the correlation between FCL and protection principles reported in section 4 are referencing to these sub-cases “FCL inside” and “FCL outside” as a generic concept.

1.4 Framework of investigations

Because of the diversity of supposable variants, it has been agreed to apply the following restrictions and assumptions to this investigation.

A typical medium voltage substation configuration with incoming and outgoing feeders and one bus tie connection is considered as an example shown in the box marked in Figure 5. Three different FCL locations indicated as L1, L2 and L3 are of typical practical relevance.

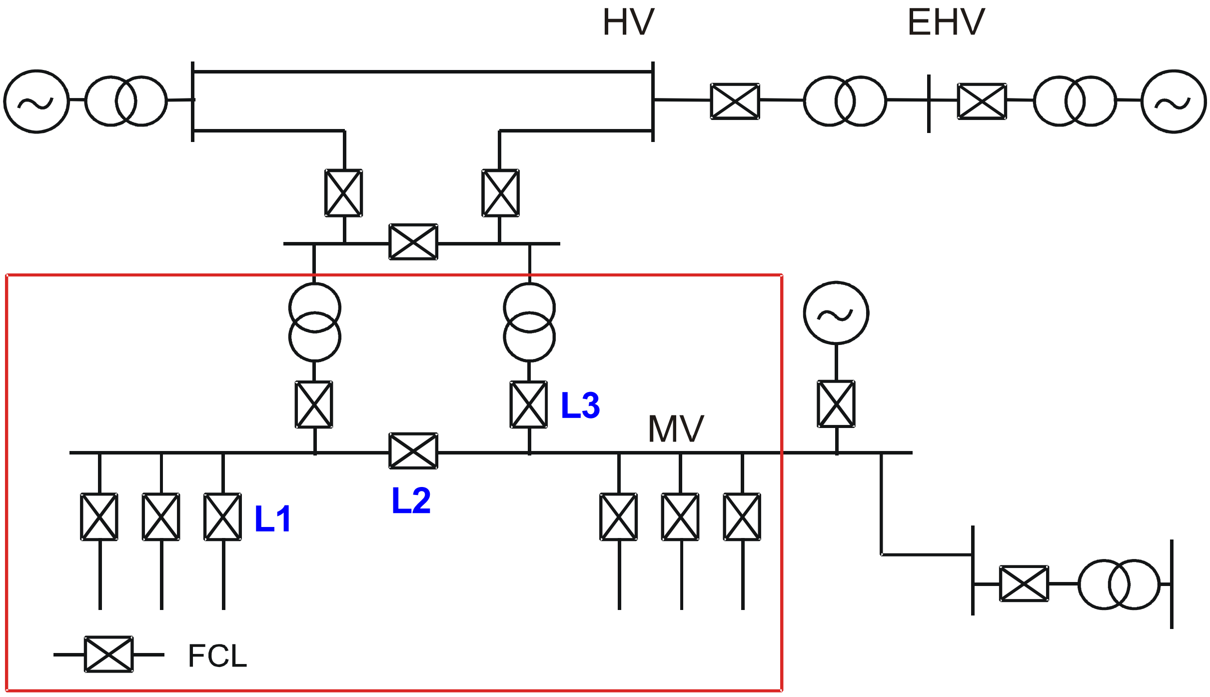

Figure 5 Example of a typical system configuration used for this guideline document

Additional restrictions and assumptions have been applied to this investigation as follows:

- The “FCL stand-alone installation” has been considered (see Figure 1).
- Only <u>one</u> FCL per subsystem and no interactions between several FCLs have been investigated (exception: fuses on outgoing feeders, see section 3.)
- The basic protection principles presented in section 1.3 were considered.

- The sub-item "sensing" of section 1.3.6 has not been considered.
- The scope of FCL types under consideration is defined by the technical report of WG 13.10.
- Faults to be discussed are located inside the primary protection zone of the corresponding relay. For the differential protection principle 87 we also considered faults located outside of the protection zone as external faults.
- Only faults activating the FCL have been considered (exception: an FCL reactor is permanently in the system any fault downstream will "activate" such a device).
- High impedance faults have not been considered since the FCL is unlikely to act.
- Because only medium voltage systems are considered, and because they are mostly high impedance grounded or non-grounded, only phase-to-phase faults have been investigated. In general, most difficulties of protection systems due to FCLs can be expected during faults affecting the positive-sequent and negative-sequent system like phase-to-phase currents, because this is causing a rather "unusual" short circuit behavior. Limited fault currents containing zero sequent components such as phase-to-ground faults are well known standard conditions of medium voltage systems with typical limiting devices applied to the star point connection of transformers. That is why it is not expected that phase-to-ground faults will raise urgent protection problems regarding FCL applications.
- Unbalanced fault current limitation is not considered here. This effect could be based on different action times, different rate of recovery, different post fault impedances etc. of the FCL. Unexpected currents and voltages can be produced and the plausibility tests of the protection relays can be disturbed which leads to a blocking of the relays.
- Malfunctioning of the FCL has not been considered.
- Ability of the FCL to reset immediately or shortly after fault clearing is only of concern for reclosing operations which is beyond the scope of this report.
- Transient over voltages caused by FCL action are not considered.

The above mentioned restrictions and assumptions allow a simplified but useful basic investigation and must be kept in mind when applying the results reported in this guideline.

2 Short-circuit behavior of different kind of FCLs

Figure 6 shows the wave shape of a typical unlimited fault current as well as the influence on this wave shape if FCL devices with and without fault current interruption capability are applied to the system. Furthermore, some of the basic data described in the Technical Brochure No. 239 by Cigre WG A3.10 [1], which characterize the limiting behavior of an FCL and which can be used as a guide to specify an FCL device, are also presented in Figure 6.

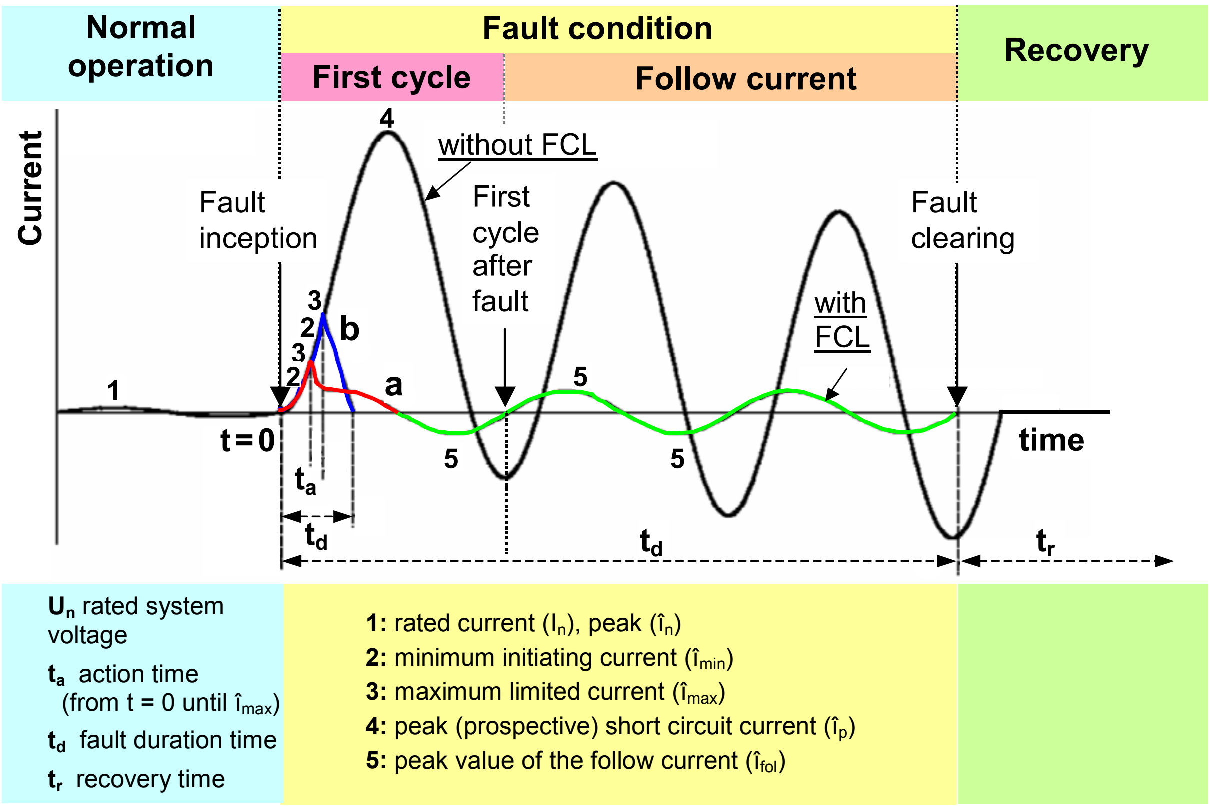

Figure 6 Typical fault current wave shape and characteristic data:

***a**: FCL without fault current interruption; **b**: FCL with fault current interruption*

A distinction among the different types of fault current limiting measures is made between “Permanent impedance measures” and “Conditional impedance measures” as illustrated in Figure 7. Permanent impedance measures make use of a permanent increase of the source impedance, both at normal and at fault conditions, whereas conditional impedance measures bring about a fast increase of the source impedance only during fault conditions. The Technical Brochure No. 239 by Cigre WG A3.10 [1] has originally introduced the terms “passive” and “active” measures for this systematic. In this context, “passive” describes measures of permanent increase of impedance during normal load and fault current conditions. The term “active” describes all measures (e.g. FCLs) which change their impedance between normal load and fault conditions. The terms “passive” and “active”, while of lesser precision in describing the systematic in Figure 7, are carried over into this report only to allow the reader to recognize them in past publications and presentations.

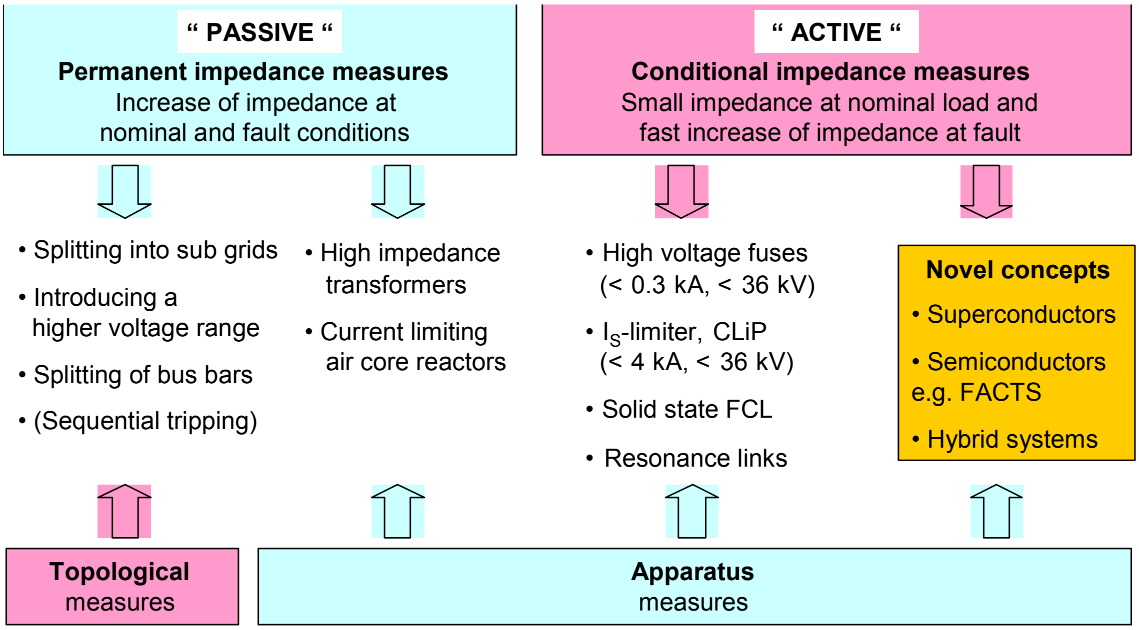

Figure 7 Systematic overview of fault current limiting measures

However, during the investigations of this new WG A3.16, which focuses on the impact of FCLs on protection, it was found that the terms “active” and “passive” are better be used to describe the mechanism by which the follow current is controlled. Therefore, regarding the purposes of this work (influence on primary protection), FCLs can be categorized as illustrated in Figure 8 .

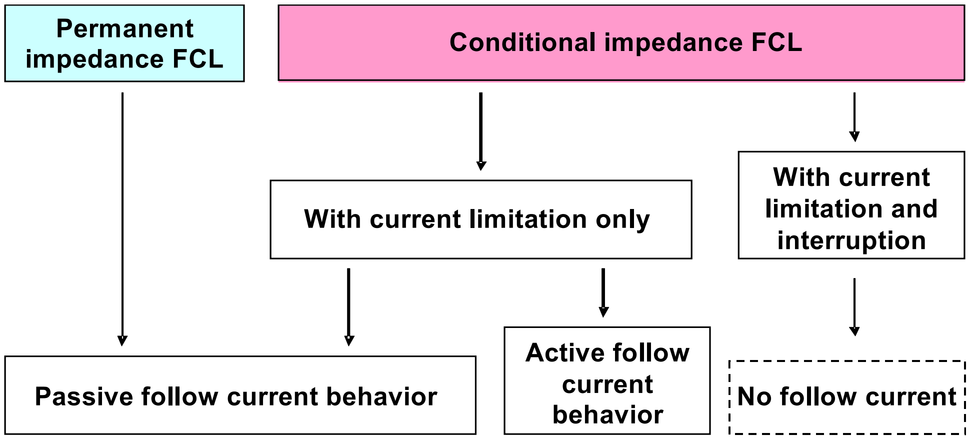

Figure 8 Categories of FCLs with respect to their follow current behavior

For the purpose of the present work the different types of FCLs have been considered only with respect to their “black box behavior”, independent from their physical structure or their specific modes of operation. The behavior of FCLs during the limitation process such as

- Amplitude of follow current remains stationary or is variable
- Distortion of follow current’s wave shape

has an impact on protection and must be considered appropriately. For example, a resistive type superconducting FCL is a conditional impedance FCL with current limitation only and passive follow current behavior (once the superconductor quenches the current flows primarily in the bypass shunt and the device behaves like a constant (i.e. “passive”) impedance. In contrast, a solid state FCL is also a conditional impedance FCL with current limitation only[1] but active follow current behavior (the follow current is determined by phase angle controlled and can be changed in its amplitude on a half-cycle by half-cycle basis). Another example of this category is a diode-bride type FCL where the user has active control over the bias current and therefore may adjust the follow current actively. A pyrotechnical fuse type FC such as the Is-limiter will therefore be categorized as a conditional impedance FCL with current limitation and interruption. Finally, a further distinction can be made between FCLs with inherent trigger mechanism (i.e. a resistive type superconducting FCL) and those with forced trigger mechanism (i.e. the Is-limiter).

To qualify the influence of FCLs on protection systems the behavior of the different kinds of FCLs during a fault must be known. Since the signal processing of protection systems is

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[1] The solid state FCL may also be designed to interrupt the current without follow current flow.

often based on a cycle-by-cycle analysis (even with sliding windows) it will be necessary to explicitly distinguish between the “first cycle behavior” and the “follow current behavior” as illustrated in Figure 6. The first cycle behavior is determining the pickup performance of the relay. The pickup unit is commonly based on the fundamental 50/60-Hz-component during the first cycle. For that purpose, a Fourier filter algorithm is widely applied. Also the true root-mean-square (RMS)-value can be employed for pickup considering all harmonic content of distorted signals which is particularly utilized for thermal overload protection.

Both, the fundamental 50/60-Hz-component and the true RMS-value are averaged values which depend on the specific time domain waveform. For signals significantly distorted from the sinusoidal the fundamental 50/60-Hz-component can be noticeable deviating from the true RMS-value. Normally, the fundamental 50/60-Hz-component becomes smaller than the true RMS-value. For undistorted signals the fundamental 50/60-Hz-component and the true RMS-value will be processed as equal (considering 1/√2 of the fundamental, of course). It shall be noted that the averaged current value will change over time within this first cycle depending upon the FCL characteristics and the size of the sliding window used in the averaging algorithm. This phenomenon is illustrated in Figure 9. It shows the simulated time domain waveform of a thyristor-based solid state FCL (SSFCL) which utilizes phase angle control to maintain a through fault current for protection coordination. It becomes evident that the signals of three differently averaged current values (True RMS, Peak/sqrt(2), and Fundamental) for the distorted current waveform are not only different at the steady state follow current but also exhibit different time evolutions within the first cycle.

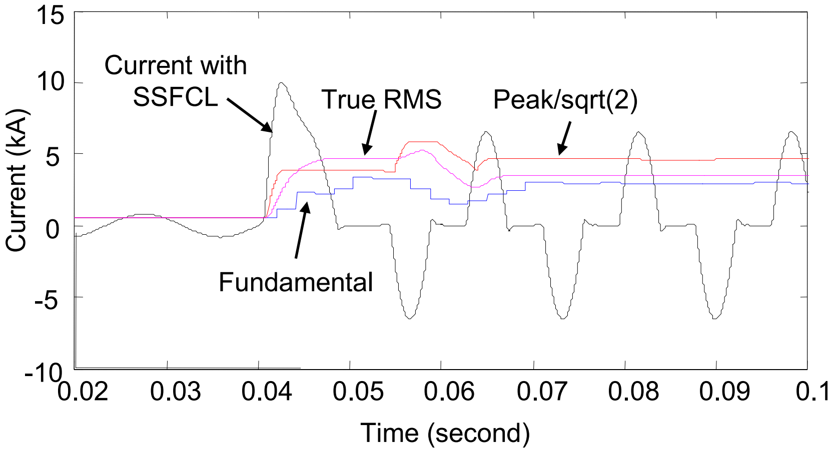


Figure 9 Simulated time domain current signals due to phase angle control of a solid state FCL (SSFCL): line current and three differently averaged current values of the distorted current waveform

For speeding up the pickup of advanced relays, only fractions of a cycle may be used by employing special digital filtering algorithms. These are also called booster algorithms. Furthermore, high-speed pickup and tripping facilities, e.g. for switch-on-to-fault or busbar differential protection, are most often based on instantaneous values. In this case, pickup and tripping times of few milliseconds are achievable. Therefore, the follow current behavior with respect to the relay measurement function significantly determines the post pickup performance of the relay. In case of strongly distorted first cycle signals, evolving faults, delayed tripping based on time grading etc., the follow current behavior will be evaluated by the relay algorithm accordingly.

In conclusion the following systematic is established:

Qualifying criteria of FCLs:

A First cycle behavior (with respect to the relay measurement function)

1. Minimum initiating current (instantaneous value)
2. Action time t_a
3. Averaged current (with respect to the measurement function, i.e. in most cases this would be the fundamental 50/60-Hz-component)
4. X/R ratio of total fault loop

B Follow current behavior (with respect to the relay measurement function)

1. Averaged current (with respect to the measurement function, i.e. in most cases this would be the fundamental 50/60-Hz-component)
2. X/R ratio of total fault loop
3. Current distortion

C Maximum allowable fault duration time

2.1 Examples:

Typical values are given in the examples below.

2.1.1 Permanent impedance fault current limiter

Fault current limiting reactor

A First cycle behavior
  1 Minimum initiating current: N/A (not applicable)
  2 Action time: N/A
  3 Averaged current: large multiple of nominal current, no distortion
  4 X/R ratio of total fault loop: not changing

B Follow current behavior
  1 Averaged current: large multiple of nominal current
  2 X/R ratio of total fault loop: not changing
  3 Current distortion: none

C Maximum allowable fault duration time: typically 1 - 3 seconds

2.1.2 Conditional impedance fault current limiter with current limitation only

Superconducting fault current limiter (resistive type)

A First cycle behavior
  1 Minimum initiating current: small to large multiple of rated current
  2 Action time: few milliseconds
  3 Averaged current: expected only low waveform distortion
  4 X/R ratio: R increasing, DC offset reduced

B Follow current behavior
  1 Averaged current: expected to be less than first cycle value
  2 X/R ratio: R increasing, DC offset reduced
  3 Current distortion: none

C Maximum allowable fault duration time: several cycles (depends on degree of limitation)

Solid-state fault current limiter (with phase angle control for follow current)

A First cycle behavior

1 Minimum initiating current: small to large multiple of rated current
2 Action time: less than one millisecond
3 Averaged current: significant waveform distortion is expected
4 X/R ratio: R increasing, DC offset reduced

B Follow current behavior

1 Averaged current: expected less than first cycle value
2 X/R ratio: system-inherent value
3 Current distortion: significant (due to phase angle control)

C Maximum allowable fault duration time: possibly up to continuous operation (depends on FCL design requirement)

2.1.3 Conditional impedance fault current limiter with current limitation and interruption

Pyrotechnic fault current limiter

A First cycle behavior

1 Minimum initiating current : 2 times rated current or higher
2 Action time: less than one millisecond
3 Averaged current: significant waveform distortion
4 X/R ratio: R increasing (during arcing)

B Follow current behavior

1 Averaged current:	none
2 X/R ratio:	N/A
3 Current distortion:	N/A

C Maximum allowable fault duration time: FCL active: no follow current
FCL blocked: 3 seconds

Table 1 summarizes the different kind of FCLs considered in this guideline with their qualifying criteria with the above example FCLs as representatives of each kind.

From the discussion above it becomes evident that some of the new FCL devices may introduce new types of switching transients and/or voltage/current distortions during or after a trip. Therefore, a strong desire will exist in the future to model and simulate these FCLs operating in networks to a high degree of accuracy, particularly for protection coordination studies. Additional information about simulation issues of FCLs can be found in the Appendix B.

Kind of FCLs **Qualifying criteria**	2.1.1 Permanent impedance fault current limiter **(PASSIVE)**	2.1.2 Conditional impedance fault current limiter with current limitation only **(ACTIVE)**		2.1.3 Conditional impedance fault current limiter with current limitation and interruption
	Fault current limiting reactor	**Superconducting fault current limiter** (resistive type)	**Solid state fault current limiter** (phase angle control for follow current)	**Pyrotechnic fault current limiter**
A First cycle behavior				
1: Min. initiating current	N/A	small to large multiple of rated current	small to large multiple of rated current	2 times rated current or higher
2: Action time	N/A	few milliseconds	less than one millisecond	less than one millisecond
3: Averaged current	large multiple of nominal current, no distortion	only low waveform distortion	significant waveform distortion	significant waveform distortion
4: X/R ratio	not changing*	R increasing, DC offset reduced	R increasing, DC offset reduced	R increasing (during arcing)
B Follow current behavior				
1: Averaged current	large multiple of nominal current	expect less than first cycle value	less than first cycle value	none
2: X/R ratio	not changing*	R increasing, DC offset reduced	system-inherent value	N/A
3: Current distortion	none	none	significant due to phase angle control	N/A
C Maximum allowable fault duration time	1-3 seconds	several cycles (depends on degree of limitation)	possibly continuous operation (depending on FCL design requirements)	FCL active: No follow current FCL blocked: 3 seconds

Table 1 Different kind of FCLs and their qualifying criteria

*: X/R ratio of fault current limiting reactors is not changing during a limitation action

3 Analysis and structuring of protection systems

3.1 Application of the zone concept

For analyzing the impact of an FCL on a given protection system, the network configuration including the FCL and the protection system has to be structured preferably according to the zone concept introduced in section 1.3.7. The protection base designs or protection single line diagrams of the network to be investigated should be the best basis to proceed. The transfer of the given protection single line diagram to a zone-concept version should be the first step to perform this investigation.

Exemplary, the red-marked network structure of Figure 5 has been transferred and completed according to the zone concept. Figure 10 , Figure 11 , Figure 12 and Figure 13 of section 3.2 show the resulting schematics. Three FCL locations L1, L2 (feeder with 21), L2 (feeder with 50/51) and L3 have been considered. The assignment of the protection principles to the network devices and elements has been done according to a standard protection philosophy.

The network consists of two incoming feeders with HV/MV-transformers, a sectionalized MV-busbar and outgoing feeders. The HV/MV-transformers are protected by the protection principle 87-Low. The incoming feeder of the MV-busbar provides the principle 50/51 which is delayed by 0.6 s at 50 Hz. This delay is caused by a time grading of the outgoing feeders. The bus coupler and the incoming feeders provide a selective downstream fault clearing. The directional element 67 prevents a total loss of in-feed in case of a fault on the incoming feeders. Back-feeding is neglected in this example. The voltage signal for the directional element 67 is derived from the PT connected to the MV-busbar.

The bus tie is equipped with an overcurrent relay 50/51 delayed by 0.3 s at 50 Hz according to the time grading. The outgoing feeders are protected by the distance principle 21 or overcurrent principle 50/51. The voltage signal for the distance protection 21 is derived from the PT connected to the MV-busbar. The first zone reach of the distance principle refers to 85%. This is a typical value applied with digital relay technology. The first distance zone and the overcurrent principle 50/51 are operating without delay. For completeness one outgoing feeder is protected by a HV-fuse.

Figure 10 through Figure 13 also illustrate the primary protection zones assigned to each protection principle. These zones are covering the entire network. Backup zones are not depicted. For each fault location the respective primary protection zone can be easily observed illustrating which protection principle first to clear this fault. Each FCL location also maps to its respective protection zone. This information allows determining if the sub-case “FCL inside” or “FCL outside” of Figure 3 or Figure 4 applies. Depending on the sub-case and the affected protection principle, different kind of impacts have to be considered according to the Table 2 and Table 3 of section 4.

As a reminder, all the above should only serve as an example of a typical protection system. It should not exclude other variants of protection systems for which, as a generic approach, these considerations can be applied accordingly.

3.2 Examples for illustration of the zone concept

Two examples illustrating the previously introduced concepts are given below. The figures presented in these examples result from applying the zone concept on the red-marked network structure of Figure 5 .

Example 1:

The fault marked in Figure 10 is located at an outgoing feeder protected by the distance principle 21. It lies within the primary zone of this distance principle and has to be cleared first by this protection. The FCL is located at the bus tie and outside of the respective protection zone of the fault considered. Therefore, the impact of the FCL on the distance protection principle has to be considered according to Table 2 and Table 3 of section 4 (where this example will be continued) with this fault location corresponding to the sub-case “FCL outside.

Example 2:

In Figure 11 the fault is located and protected like the one in Example 1. However, the FCL is located at the outgoing feeder. Therefore, the FCL is inside the assigned protection zone and the sub-case “FCL inside” is valid. The impact of the FCL on the distance protection can be discussed based on Table 2 and Table 3 of section 4 (where this example will be continued) applying the sub-case “FCL inside”.

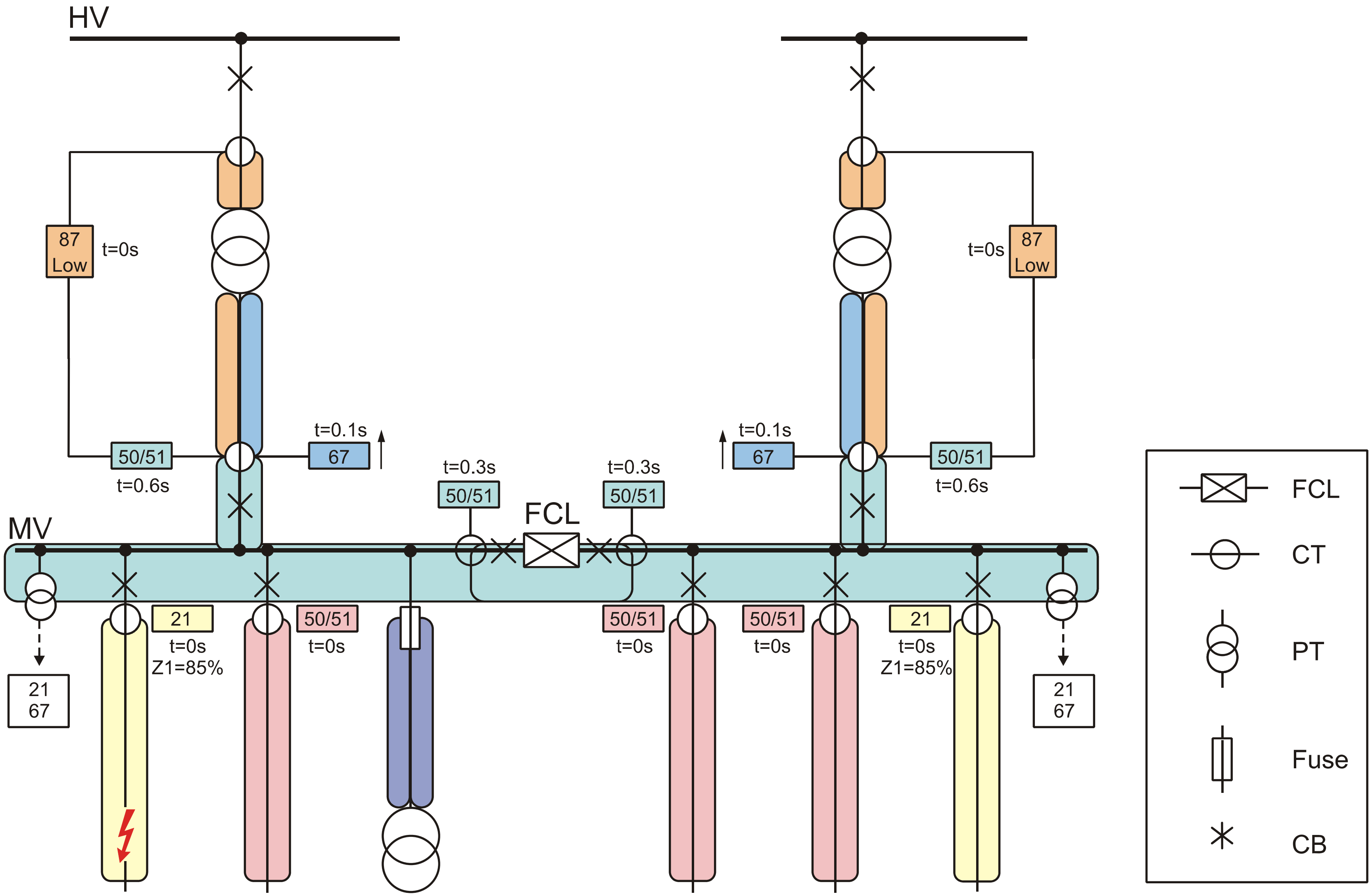


Figure 10 Example for protection system including the protection zones and FCL location L2

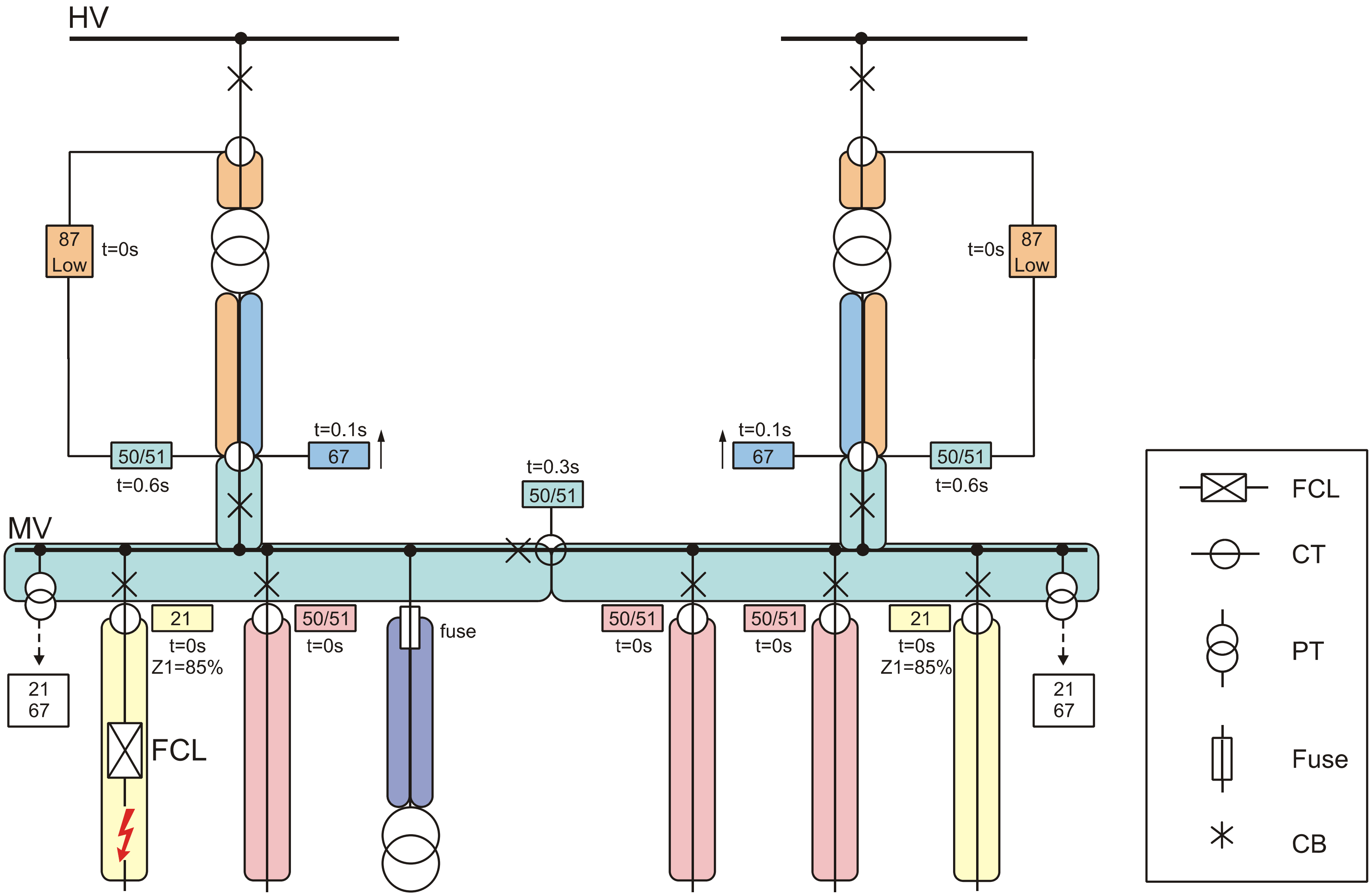


Figure 11 Example for protection system including the protection zones and FCL location L1

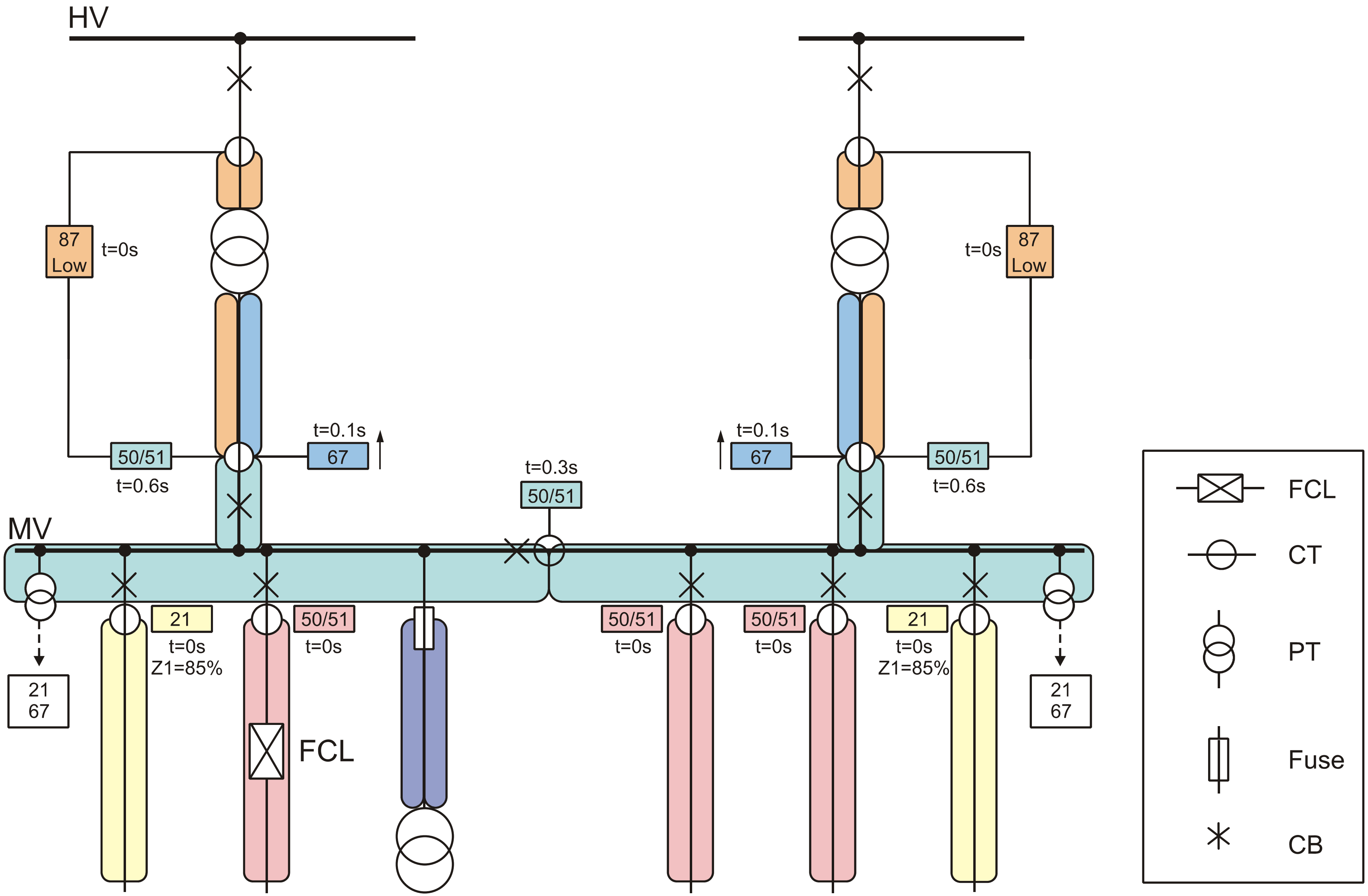


Figure 12 Example for protection system including the protection zones and FCL location L1

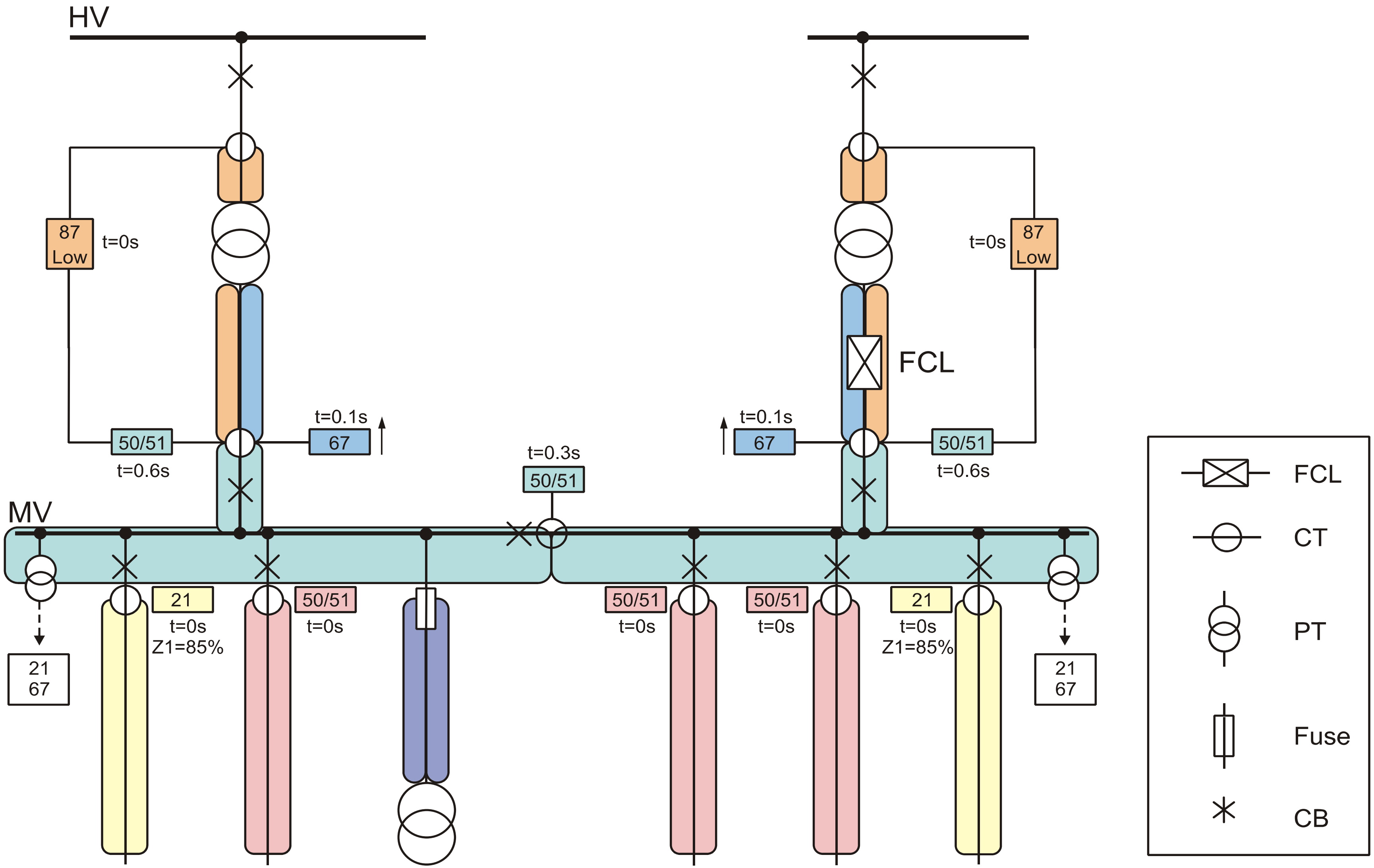


Figure 13 Example for protection system including the protection zones and FCL location L3

4 Correlation between FCL and protection system

4.1 Influences of FCLs on protection systems

The protection system is an indispensable part of each power system. It must fulfill the requirements of “sensitivity”, “selectivity”, “fast operation” or “rapidity”, and “operating reliability” in order to neither affect the electrical system performance during normal system operation nor to submit the electrical equipment to failure during the occurrence of abnormal conditions (faults). Protection systems are based on different protection principles (see section 1.3) and sub-items (see 1.3.6) ensuring an adaptive and coordinated operation in the power system. Protection coordination studies are performed to confirm the accomplishment of such requirements, especially under adverse influence from other network devices. Without this confirmation, or without a properly tested and operational protection system, a power system will be never energized.

In case of a fault, the impacts of FCLs on the protection system are represented by

- affected protection principles (see section 1.3.1 - 1.3.5),
- protection sub-items (see section 1.3.6),
- FCL location (see section 1.3.7)
- fault location (see section 3.2), and
- short-circuit behavior of different kind of FCLs (see section 2).

The evaluation of these impacts consists of two steps.

Step 1:

To evaluate the general influences between a FCL and the protection system the correlations between

- protection principles (see section 1.3),
- protection sub-items (see section 1.3.6),
- location of FCL (see section 1.3.7), and
- fault location (see section 3.2)

must be found. These correlations items (numbered from 1 to 18) are given in Table 2 for a fault fed from a single (equivalent) source (single-end in-feed condition). Thereafter, Table 3 extends this concept to the situation where the fault is fed by two sources on either end of the protection zone (two-end in-feed condition).

Step 2:

To evaluate the specific impacts of different kinds of FCLs (section 2) and the correlation items of Table 2 and Table 3. This is subject of Table 6 in section 4.3.

More detailed comments on the correlation items of Table 2 and Table 3 are listed below with their corresponding numbers.

Protection sub-item: Pickup

1) Overcurrent (50/51)

   No adverse influence as long as the minimum limited fault current measured by the relay, depending on the limitation factor and possible current distortion of the FCL, still exceeds the threshold for pickup current of the overcurrent function.

2) Directional (67)

   No influence since directional relays do not pickup by themselves. They are conjugated with overcurrent or distance relays. The pickup is based on overcurrent (see item 1) or zone impedance (see item 3).

3) Distance (21)

   The FCL is installed in series with the fault loop and thus increases the zone impedance accordingly. It has to be checked if enough zone reach ($Z_{Fault} < Z_{pickup}$) and accuracy remains. This aspect concerns both the reactive (X) and resistive (R) impedance component. Very high or low X/R-ratios (>5 or <1/5) are reducing the accuracy of the impedance determination. Since this is influenced by the X/R-ratio of the FCL its characteristics must be known.

4) Differential (87-Low)

   Differential relays can have overcurrent pickup or an over current guarding function (see item 1).

5) Differential (87-High)

   High impedance protection does not provided any pickup facility. The relay is always active. Only the differential current is physically summed up and measured by the relay.

Protection sub-item: Processing

3b) Same influence on impedance as for item 3), but related to the subitem processing and tripping zones.

6) The FCL must allow the fault current to flow at least as long as the sum of all processing times and the delay times. This depends on the fault duration time of the FCL.

7) A resistive impedance due to the FCL can reduce the X/R ratio significantly from the expected value without FCL. The system impedance phase angle can therefore be outside of the forward/backward angle sensing range. This can lead to errors in forward/backward direction evaluations.

8) Additional phase angle shifts can be introduced by signal filters in the relay algorithms (only if voltage and current filters are different). Such filtering may especially be necessary if FCLs are deployed which significantly distort the current waveform. The resulting additional phase angle shifts can lead to an influence on the determination of direction and impedance measurement depending on the current limiting technique employed by the FCL.

9) For determining direction the corresponding voltages have to be used. The FCL is supposed to increase the source impedance, ,thus the voltages of the faulty phases may become to low for sufficient measurement accuracy. A remedy in modern relays is to use the voltages from the healthy phases or the memorized (pre-fault) voltages. In the latter case the source impedance also plays a role in determining the direction and applying the zone reaches. The zone reach characteristic will be polarized based on the source impedance. The FCL effectively increases the source resistance and/or reactance. This may change the X/R-ratio of the new source impedance to be considered. The algorithm for the determining direction has to process unexpected source impedances. Wrong determination of directions or too short zone reaches can be the consequence if using existing MHO-relay algorithms are used.

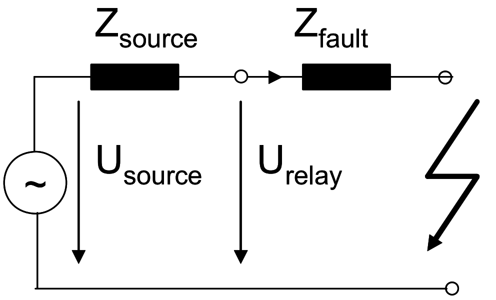
10) External fault: a positive impact on protection stability is expected because the fault current is lower than without FCL. Internal fault: insufficient sensitivity due to the reduced fault current.

11) Comment: same as item 10).

Protection sub-item: Coordination

12) There is a possibility to extend the current grading by applying a high set stage. Faults between the relay and the FCL can be cleared without a delay and hence without affecting the selectivity. On the other hand, an inter-in-feed at the next station can enlarge the blinding effect (compare Figure 3b) as the fault current contribution via the FCL is reduced. Therefore, faults beyond the next station could not longer be sensed and the relay is "blinded". This effect depends on the ratio of the FCL impedance and the inter-in-feed source impedance.

13) The source impedance ratio (SIR) as defined in Figure 14 is considerably increased due to the impedance of the FCL. Existing current grading, e.g. realized by inverse time relays, can be distorted. Re-coordination is necessary.



$$\mathrm{SIR} = \frac{Z_{\mathrm{source}}}{Z_{\mathrm{fault}}}$$

Figure 14 Definition of source impedance ratio SIR

14) Inter-in-feed generally reduces the distance protection zone. The reduction depends on the impedance which lies between the inter-in-feed and the fault. Thus, the FCL inside the protection zone, according to Figure 3b, enlarges the inter-in-feed effect which leads to under-reaching which, in turn requires re-coordination.

15) Because of the increased source-impedance and SIR, relatively low voltage values of the faulty phases have to be expected. This leads to a decreased

accuracy of measurement and the need of reach reduction, particularly of the first zone.

16) From theory, generally no coordination exists between differential protection and other protection. The exception is that a busbar differential protection, where not all the feeders are equipped with CTs (low current outgoing feeders), requires time coordination of the differential relay with the overcurrent protection of the non observed feeders (most often fuses). In such cases, due to a possibility of delayed tripping of the overcurrent protection caused by the FCL, re-coordination may be necessary.

Two-end in-feed conditions are important to be considered only for differential protection. Table 3 covers this matter. All other protection principles, discussed in this framework, are not affected by the two-end in-feed condition.

17) The effect of current amplitude reduction is expected to be less critical than with only one source. But the FCL can produce a phase angle shift between both source currents, which leads to a reduction of the differential current as a result of the vector summation of these currents. The stabilizing current, which is the scalar sum of the values, remains equal. This leads may lead to less sensitivity depending on the degree on limitation and the X/R ratio caused by the FCL.

18) The effect of current amplitude reduction is expected to be less critical than with only one source. Because no stabilizing current is processed, there is no influence caused by the different phase shift of the source currents as described in item 17).

Protection principles	Pickup		Processing		Coordination	
	FCL Inside	FCL outside	FCL Inside	FCL outside	FCL Inside	FCL outside
Overcurrent 50/51	1 : overcurrent pickup: $I_{SC\ FCL} > I_{Pickup}$		6 : FCL fault duration > processing time, additionally delay due to inverse-time characteristics		12 : current grading, current blinding	13 : source-impedance ratio (SIR) – grading
Directional functionality 67	2 : zone impedance pickup (refer to 3)		6, 7, 8 : range of line phase angles including FCL, signal distortion	6, 8, 9 : determination of direction based on source impedance	No coordination, because the directional stage is added to overcurrent or distance function	
Distance 21	1, 3 : overcurrent pickup, impedance pickup $Z_{Fault} < Z_{Pickup}$	1 : overcurrent pickup, no influence on impedance pickup	3b, 6,8: zone impedance sensing	6, 8, 9 : determination of direction based on source impedance	14 : Inter-in-feed effect	15 : source-impedance ratio (SIR) - accuracy
Differential 87-Low impedance	1, 4 : Overcurrent pickup or overcurrent guarding		6, 10 : lower fault current, check for sensitivity		16 : No coordination with other types of protection, only some unusual exceptions	
Differential 87-High impedance	5 : No overcurrent pickup facility, differential current measurement only		6, 11 : lower fault current, check for sensitivity			

Table 2 Correlations between protection principles and protection sub-items, depending on the fault location with respect to the location of the FCL
(the numbers correspond to explanations and comments in the main text)

Protection principles	**Pickup**		**Processing**		**Coordination**	
	FCL Inside	FCL outside	FCL Inside	FCL outside	FCL Inside	FCL outside
Overcurrent 50/51	See Table 2		See Table 2		See Table 2	See Table 2
Directional functionality 67	See Table 2		See Table 2	See Table 2	See Table 2	
Distance 21	See Table 2		See Table 2	See Table 2	See Table 2	See Table 2
Differential 87-Low impedance	See Table 2		6,17: Lower differential current, because of phase angle shift between the two sources		See Table 2	
Differential 87-High impedance	See Table 2		6, 18: Less impacted by amplitude reduction than with only one source. Not influenced by phase angle shift.			

Table 3 Extension of Table 2 for the “two-end in-feed” condition
(the numbers correspond to explanations and comments in the main text)

4.2 Examples for deducing the influencing phenomena

The following is a continuation of the examples introduced in section 3.2 for illustrating how to use Table 2 and Table 3.

Example 1:

The conclusion was that we have a distance protection 21 which is influenced by a fault and an FCL which is located such that the sub-case “FCL outside” applies. From Table 2 it can be derived that the following influencing phenomena, as listed in Table 4, have to be discussed. From Table 3 we conclude that there is no difference between single in-feed and two-in-feed in this case.

sub-item	**Influencing phenomena**
pickup	1
processing	6, 8, 9
coordination	15

Table 4 Correlation between protection sub-items and influencing phenomena of example 1

This assessment explains that the FCL influences the applied protection system only through the overcurrent pickup facility. If only impedance pickup is applied, no influences are to be supposed because of a large and undirectional impedance pick-up zone is assumed to be applied. However, the fault duration must be longer than the processing time. The impedance and directional determination for tripping, which must be much more precisely performed as the pick-up zones, can be adversely influenced by an unexpected increase in source impedance caused by the FCL. Hence, the relay must be able to handle such kind of source impedances and distorted signals regarding the algorithm for impedance and directional determination. The protection coordination is endangered by the potentially reduced accuracy of the voltage measurements caused by the increased source impedance ratios. Modifications of settings could be necessary. This example will be continued in section 5 to incorporate the qualifying criteria of FCLs defined in section 2.

Example 2:

The conclusion of this example was that we have a distance protection 21 which is influenced by a fault and an FCL which is located such that the sub-case “FCL inside” applies. From Table 2 it can be derived that the following influencing phenomena listed in Table 5 have to be considered. Table 3 does not bring any new information because there is no difference between single in-feed and two-in-feed in this case.

sub-item	**Influencing phenomena**
pickup	1,3
Processing	3b,6,8 (7; if 67 is an integral part of protection 21)
coordination	14

Table 5 Correlation between protection sub-items and influencing phenomena of example 2

That means that the FCL influences the applied protection system through the overcurrent and impedance pickup facility. The fault duration must be longer than the processing time. Furthermore, the zone impedance measuring and determination of direction can be adversely influenced by a phase angle shift, signal distortion, and additional impedances The protection coordination is endangered by a possibly enlarged inter-in-feed effect (compare Figure 3b). This example will be continued in section 5 to incorporate the qualifying criteria of FCLs defined in section 2.
Whether these influences actually apply for any given type of FCL will be discussed in the next section.

4.3 Correlation between influences and qualifying criteria

The correlations between the influencing phenomena, as the results of the Table 2 and Table 3, and the qualifying criteria from Table 1 are presented in Table 6. The numbering of the influencing phenomena (listed vertically) and qualifying criteria (listed horizontally) is according to the previous sections. An “X” means that the corresponding influencing phenomenon has to be considered for that particular qualifying criterion whereas an empty field means no influence.

Qualifying criteria / Influencing phenomena	First cycle				Follow current			
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**C**
	Minimum initiation Current	Activation Time	Averaged Current	X/R Ratio	Averaged Current	X/R Ratio	Current Distortion	Max Fault Duration
Pickup								
1,2: Overcurrent pickup	X	X	X		X		X	X
3: Impedance pickup			X	X				
4: Overcurrent guarding	X	X	X		X		X	
5: Pickup of high impedance protection	No pickup facility, no influence							
Processing								
3b: Impedance zone					X	X		
6: FCL fault duration > processing time								X
7: Ph. angle range of dir. determination						X		
8: Ph. angle shift of distorted signals							X	
9: Polarizing based on source impedance						X		
10,11: Stability and sensitivity					X		X	
17,18: Over stabilization						X	X	
Coordination								
12: Current grading and current blinding					X			
13: Current grading based on SIR					X			
14: Inter-in-feed					X	X		
15: Reduced accuracy based on SIR					X			
16: Coordination of differential protection	No coordination, no influence							

Table 6 Correlations between the influencing phenomena from Table 2 and Table 3 and the qualifying criteria from Table 1.

The above correlations are based on a common protection relaying model consisting of a pickup and processing unit and standard coordination methods. It should be noted that all deviating relaying models and applications, e.g. those with a merged pickup and processing unit or those with self coordinating facilities, may lead to a different correlation table.

5 Practical use of this guide

This section shows how to apply the developed methods concisely to practical examples. Thus, examples of FCL applications and their influence on the protection system will be discussed in general terms. These discussions are mainly based on the Table 2, Table 3 and Table 6.

5.1 Continuation of the examples of section 3.2 and 4.2

Example 1:

The conclusions so far demonstrated the correlations between the protection sub-items and influencing phenomena according to Table 4.

Using Table 6 we are now able to deduce the qualifying criteria of the FCL for this example and hence extend Table 4, Table 5 and Table 7.

Sub-item	Influencing phenomena	Qualifying criteria
pickup	1	A1, A2, A3, B1, B3,C
processing	6, 8, 9	C, B3, B2
coordination	15	B1

Table 7 Correlation between the protection sub-items, influencing phenomena, and qualifying criteria of example 1

In case of a fault current limiting reactor the specific qualifying criteria can be found in Table 1.

Based on that, the statement regarding the protection sub-item “pickup” will be as follows:

The criteria A1 and B1 indicate a large multiple of nominal current. Thus, no problems during the first and the following cycles are expected regarding an overcurrent pickup facility. The allowable fault duration time of 1-3 seconds (criterion C) should be longer than the longest necessary pickup duration. Thus, no danger of a pickup reset before tripping is given. Criteria A2, A3 and B3 are of no concern in this case.

The statement regarding the protection sub-item “processing” follows as:

The criterion C should be long enough for the longest required processing period. B2 and B3 are of no concern in this case.

Finally, the statement regarding the protection sub-item “coordination” follows as:

The criterion B1 indicates a large multiple of nominal current, which means a lower degree of limitation. Thus, reduction of accuracy is not expected. The first zone reach in forward direction can remain unchanged. To summarize this example: influences of the FCL type fault current limiting reactor on the protection system are given but the protection operation remains most likely undisturbed.

Example 2:

The results so far were the correlations between the protection sub-items and influencing phenomena according to Table 5.
Using Table 6 we can now deduce the qualifying criteria of the FCL to be discussed and extend Table 5 to Table 8.

sub-item	Influencing phenomena	Qualifying criteria
Pickup	1	A1, A2, A3, B1, C
	3	A3, A4
Processing	3b	B1, B2
	6	C
	8	B3
	7; if 67 is an integral part of protection 21	B2
Coordination	14	B1, B2

Table 8 Correlation between the protection sub-items, influencing phenomena and qualifying criteria of example 2

In case of a superconducting fault current limiter (resistive type) the specific qualifying criteria can be found in Table 1. Based on that, the statement regarding the protection sub-item "pickup" follows as:

Overcurrent (criterion 1) and impedance (criterion 3) pickup must be distinguished. The criteria A1, A3 and B1 due to the overcurrent pickup indicate that I_{sc} is a small to large multiple of rated current. Problems will arise if the first cycle fault currents are limited to values in the range of the rated current. Because of A2, there is very little time for a current pickup based on the unlimited fault current. Additionally, criterion C may cause a reset of pickup before tripping. The impedance pickup is disturbed by the criteria A3 and A4. The measured impedance will be unexpectedly high with a large resistive component. This must be considered by the protection settings.

The statement regarding the protection sub-item "processing" follows as:

The impedance zone reach measurement is disturbed by criteria B1 and B2. The measured impedance will be unexpectedly high with a large resistive component. This must be considered by the protection settings. In the worst case, it might be out of range of the allowable settings. Thus, the relay might not be able to cover the line beyond the FCL. The criterion C should be long enough for the longest required processing period. In this case, a fairly short processing period is required. Booster algorithms could be applied to mitigate the problem. Criterion B3 is of no consequence, but criterion B2 can lead to unexpectedly low fault impedance angles (high resistive component) which can not be declared definitely as forward or backward faults. A re-adjustment of the angle range of the directional determination may be necessary.

The statement regarding the protection sub-item "coordination" follows as:

Criterion B1 is enlarging the inter-in-feed effect considerably due to the expected high degree of limitation. Additionally, the fault impedance angle becomes unexpectedly low because of criterion B2. The zone reach must be adapted accordingly, but it might be out of the range of the allowable settings. Thus the relay might not be able to protect the line beyond the FCL.

To summarize this example: influences of a (resistive type) superconducting FCL on the protection system are evident. These lead to severe consequences which may not permit an undisturbed protection operation. At minimum, changes of relay settings may have to be performed.

5.2 Application example – IPP integration

A typical application example for the utilization of an FCL is the interconnection of an IPP in-feed to an existing system. Figure 15 shows the network scheme of such an application example. Additional in-feed from the downstream feeders is not assumed. According to the classification of the FCL application methods in Figure 1 this example represents the case of an FCL stand-alone installation.

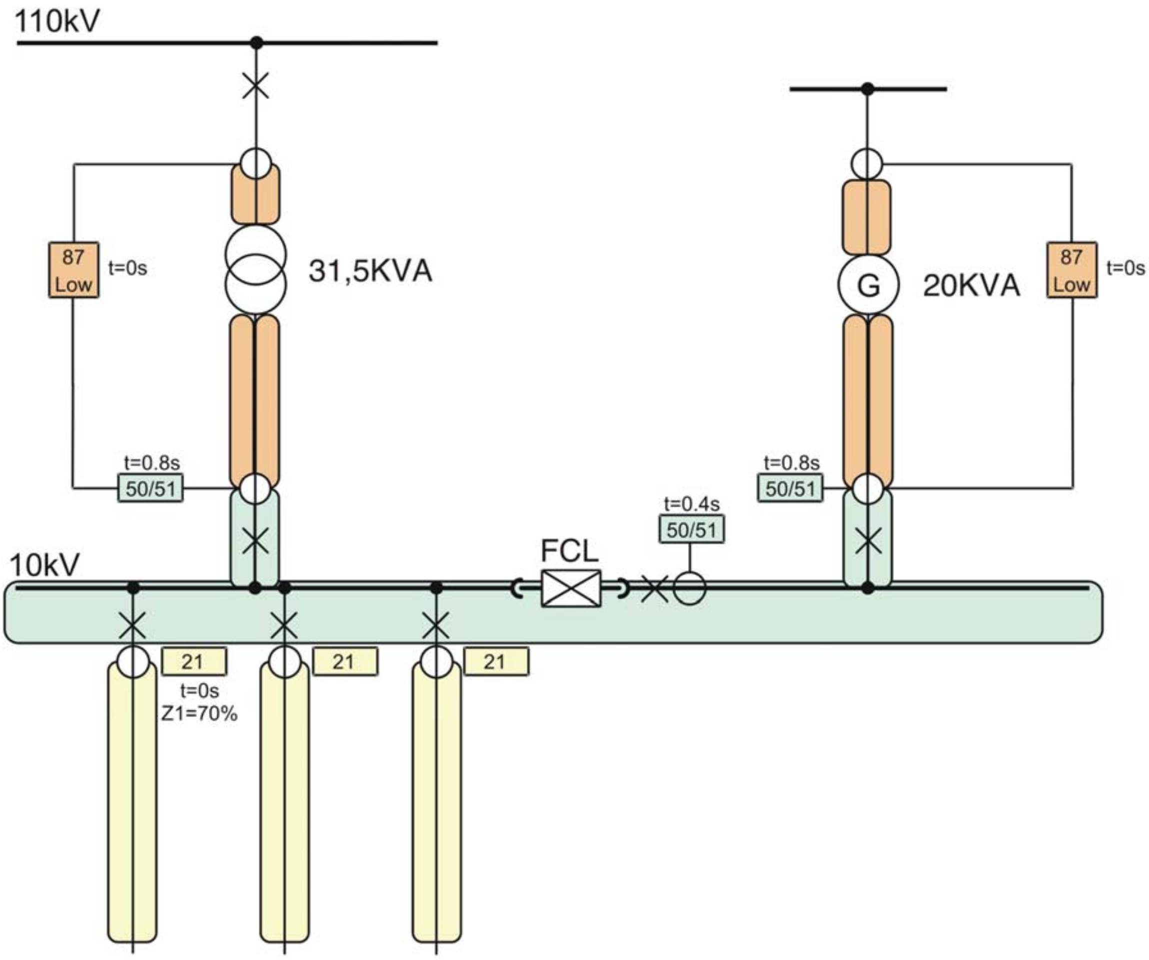


Figure 15 Network scheme of the application example “IPP integration”

Figure 15 contains the corresponding network devices including the FCL. Additionally, the primary protection zones according to the definitions of section 1.3.7 and the appropriate protection principles are shown. Therefore, the following protection principles will be investigated: 87-Low, 21, 50/51 in-feed and 50/51 bus coupler. On the basis of symmetry the principles 87-Low and 50/51 each need to be investigated only one time.

Following the framework of section 1.4, faults to be discussed are located inside the primary protection zone of the corresponding relay and should activate the FCL. For the differential protection principle 87 we also considered faults located outside of the protection zone as external faults. Thus, the fault locations, which are relevant for these considerations, lie beyond the FCL regarding the location of the corresponding protection device and vice versa. For the protection principle 87-Low internal faults inside the protection zone and external faults, which are activating the FCL, will be discussed. Faults, which are not activating the FCL, will be cleared uninfluenced and do not need to be discussed here.

Two types of FCL and their specific influences will be analyzed: pyrotechnic and solid-state (with phase angle control for follow current).

In the following, the influences of those two FCL types on the different protection principles applied in Figure 15 will be investigated separately and discussed step by step using the method proposed in this guide.

Protection principle 87-Low

The FCL-outside scenarios of Figure 4 a) and b) is applicable in this case. For the protection principle 87-Low, the following correlation Table 9 can be worked out.

sub-item	Influencing phenomena	Qualifying criteria
Pickup	1, 4	A1, A2, A3, B1, B3, C
Processing	6, 10	C, B1, B3
Coordination	16	-

Table 9 Correlations between the protection sub-items, influencing phenomena and qualifying criteria of the 87-Low protection principle

Pyrotechnic FCL:

Considering the min. initiating current (A1), the action time (A2) and the averaged current (A3) of this kind of FCL, the pickup during an external fault, e.g. for starting the fault recorder, will not take place in any case. Only special high-speed relay technology is able to sense such currents. Because no follow current exists (B1, B3, C), no pickup can be maintained at all. The pickup during internal faults remains unaffected as during existing system situation (i.e. before installing an FCL). Regarding processing a positive impact on external faults is given because the fault current is practically reduced to zero. Thus the fault conditions for 87-Low are able to remain stable at any case. The sensitivity to internal faults remains similar to the one observed at the existing system situation (i.e. before installing an FCL). The current conduction time is too short to influence that and no follow current exists. For differential protection no coordination is applied, thus no influence exists.

Solid-state FCL:

Considering the min. initiating current (A1), the action time (A2) and the averaged current (A3) of this kind of FCL, the pickup during external fault, e.g. for starting the fault recorder, can take place depending on the FCL control strategy. The distorted current filtered by the relay pickup facility must exceed the pickup setting. The pickup remains if the follow current (B1, B3, C) is controlled to a sufficiently large value (provided the FCL is able to conduct this current as long as it is necessary). Regarding processing a positive impact on external faults is given because the fault current is reduced in magnitude. Thus, the fault conditions for 87-Low are improved and remain stable. The sensitivity of internal faults can also be improved in relation to the existing system situation (i.e. before installing an FCL). It is depending on the averaged fault current contribution which is controlled by the solid state FCL during the fault. For differential protection no coordination is applied, thus no influence exists.

Protection principle 21

The corresponding FCL outside scenario of Figure 4 is applicable here. All of the discussed fault locations are fed from two sources, the network in-feed and the IPP. Because the network in-feed is nearly uninfluenced in this case, the IPP provides only an additional in-feed limited by the FCL.

For the protection principle 21, the following correlation Table 10 can be worked out.

sub-item	**Influencing phenomena**	**Qualifying criteria**
Pickup	1	A1, A2, A3, B1, B3, C
Processing	6, 8, 9	C, B3, B2
Coordination	15	B1

Table 10 Correlations between the protection sub-items, influencing phenomena and qualifying criteria of the 21 protection principle

Pyrotechnic FCL:

Considering the minimum initiating current (A1), the action time (A2), and the averaged current (A3) of this kind of FCL, the current pickup will be unaffected and remains as during the existing system situation (i.e. before installing an FCL). Only special high-speed relay technology is able to sense such currents. The FCL outside scenario is not influencing the impedance pickup as already mentioned in example 1 of section 4.2. Because no follow current exists (B1, B3, C), neither current neither impedance pickup can be influenced at all. Regarding processing (C, B2, B3) no influence can be stated because a follow current will not occur. Regarding coordination (B1) also no influence exists.

Solid-state FCL:

Considering the minimum initiating current (A1), the action time (A2), and the averaged current (A3) of this kind of FCL, the current pickup may be supported depending on the FCL control strategy. The FCL outside scenario is not influencing the impedance pickup. The pickup is steadily supported if the follow current (B1, B3, C) is controlled to a sufficiently large value (provided the FCL is able to conduct this current as long as it is necessary).

Remark: In principle the FCL outside scenario is not influencing the impedance pickup. However, in the exemplary case of a solid-state FCL additional phase angle shifts may be introduced by signal filters in the relay algorithms. Such filtering is necessary in the case of significantly distorted current waveforms. This can lead to an influence on the determination of the impedance measurement. Assuming that the impedance area for pickup purposes is properly (large and undirectional) chosen it is expected that this effect can be neglected in most practical cases.

Regarding processing the solid state FCL must be able to conduct the current as long as it is necessary considering the sum of all processing and delay times (C). The specific control strategy employed in the FCL results in certain severity of current distortion and effective X/R-ratio of the in-feed (B2, B3). It must be checked if unallowable phase shifts for the impedance measurement for tripping and X/R-ratios for directional determination might be produced. Because of the uninfluenced network in-feed the resulting source impedance will be least reduced by the FCL (B1). Thus, no adverse impact on the SIR and on the coordination can be expected.

Protection principle 50/51

The two protection principles 50/51 in-feed and 50/51 bus coupler will be discussed on a common base. In case of 50/51 in-feed the FCL inside scenario and in case of 50/51 bus coupler the FCL inside scenario and FCL outside scenario is applicable.

For the protection principle 50/51 in-feed and 50/51 bus coupler, the following correlation Table 11 can be worked out.

sub-item	**Influencing phenomena**	**Qualifying criteria**
Pickup	1	A1, A2, A3, B1, B3, C
Processing	6	C
Coordination	12,13	B1

Table 11 Correlations between the protection sub-items, influencing phenomena and qualifying criteria of the "50/51 in-feed" and "50/51 bus coupler" protection principle

Pyrotechnic FCL:

Considering the min. initiating current (A1), the action time (A2) and the averaged current (A3) of this kind of FCL, a pickup will not take place. Only special high-speed relay technology is able to sense such currents. Because no follow current exists (B1, B3, C), no pickup can be maintained at all. Regarding processing (C) no influence can be stated because a follow current will not occur. Regarding coordination (B1) also no influence exists.

Solid-state FCL:

Considering the minimum initiating current (A1), the action time (A2), and the averaged current (A3) of this kind of FCL, the pickup can take place depending on the FCL control strategy. The distorted current filtered by the relay pickup facility must exceed the pickup setting. Regarding processing the pickup remains if the follow current (C) is controlled to a sufficiently large value (provided the FCL is able to conduct this current as long as it is necessary). Current grading is not applied in the existing network. That is why there is no influence in case of the FCL inside and outside scenario (B1).

This example shows that the influences of FCL on protection systems can be analyzed on a systematically and holistic manner which can yield reliable results of further investigations on the identified difficulties.

6 Summary and Conclusion

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

A consequence of this development is that in certain parts of the networks the short-circuit currents approach, or even exceed, the allowable values based on equipment rating, primarily circuit breaker interrupting capability. The problem of excessive short-circuit currents has therefore become an import issue for the operators of power systems and there are clear indications for a growing interest in fault current limiting devices rated for applications in the high voltage system. But up to now, with a few exceptions, there has been relatively little progress in developing suitable devices and bringing them to the market. Only in recent years have several successful field and large scale laboratory tests with novel FCL devices been conducted which indicate significant advancements towards commercial applications. However, before FCLs will be deployed in the utility market the interaction between these new devices and the power system network, in particular the existing protection system, must be well understood. The guidelines presented in this document establish a first frame work for accomplishing this task.

Starting with a limited scope on typical medium voltage system structures this guide first reviews the most relevant system protection techniques such as overcurrent, distance, differential, and directional protection in the context of FCLs.
The chapter following establishes qualifying criteria for the different FCL technologies with respect to the application of system protection. Of particular relevance is the FCL behavior in the network with respect to the relay measurement function (first cycle and follow current).
The zone concept is reviewed and applied to differentiate the various locations of faults with respect to the FCL location. This is the first step to establish a framework which correlates the influences of different FCL measures, characterized by their

previously discussed qualifying criteria, to the various protection functions. A series of examples are discussed in detail to illustrate the new framework.

It is concluded that while FCLs will, in general, interact with the existing protection system the presented methodology helps to clearly identify the specific conditions for which such interactions occur. This framework can be generally applied since it is not restricted to the example cases presented in this document. However, additional work is required to expand the scope of the framework to high voltage systems.

7 References

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APPENDIX A

Questionnaire

A questionnaire was sent out in November 2003 from Cigre WG A3.16 asking for typical structures of distribution systems, type of protection used in the networks as well as for the need of limitation of short circuit currents in MV and HV networks.

The questionnaire and the main results are presented in this Appendix.

Based on the respond of 53 answers from 14 different countries electromechanical relays are mostly installed in the electrical systems. Electronic or digital protection will be installed more or less in the future in case of new installations only. The main protection principles used are distance, differential and over-current protection.

Evaluation questionnaire WG A3.16

questionnaires received	53
different countries	14

Brazil	6	
Argentina	1	South America 8
Venezuela	1	
Australia	6	Australia 6
Switzerland	10	
Germany	9	
Sweden	1	Europe 25
Italy	4	
Spain	1	
Japan	4	
Thailand	1	Asia 7
South Korea	2	
USA	5	
Canada	2	North America 7

Compared to the survey carried out in 1996 the answers of the questionnaire show an increase of need for short circuit current limitation especially in the HV level of 110 kV to 145 kV. Only 26 % of the answers indicate no need in general for fault current limitation. A need without restrictions was indicated by 47 % of the answers for MV and from 21 % for HV level. A need with restrictions or comments like costs, reliability, references stated 10 % for MV and 6 % for HV level. Figure 19 presents the results in graphical form.

need	**no**	**yes**	**yes (?)**
all	26 %	╳	╳
MV < 110 kV	╳	47 %	10 %
HV ≥ 110 kV	╳	21 %	6 %

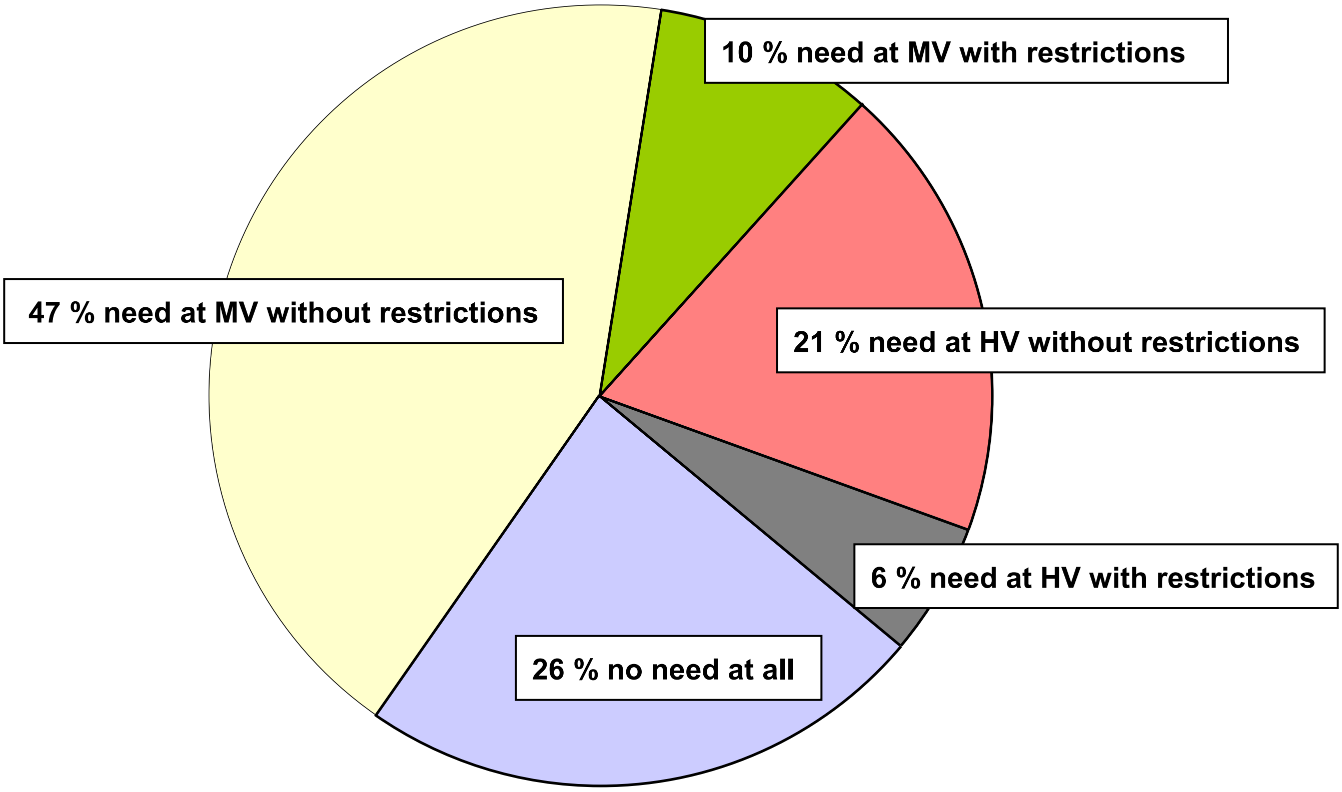

Figure 16: Results of the questionnaire - need for Fault Current Limiters

Questionnaire

1. Please submit as an example the simplified structure or configuration (single line diagram, schematic topology, etc.) of a typical distribution network or substation (including the structure of an outgoing feeder) in your region or country.
   Examples for information of utility and/or industrial networks as requested here are given in the attached file networks_Cigre_WGA3-16.pdf.

2. Please submit a representative example of a protection single line diagram for such a typical substation and/or feeder.

3. Are there fundamental differences in the structures and the protection concepts of networks and substations depending on:
   - urban or rural area
   - utility (residential) or industry.

   What are these differences? Please submit examples.

4. Which of the following protection do you use?
   - overcurrent
   - differential
   - distance
   - others

   Please explain the major applications of the different protection methods in your system.

5. Which type of protection devices do you use primarily?
   - (electromechanical) relay
   - electronic protection (analog)
   - digital protection (electronic or microprocessor based)

6. Do you have a need for limitation of short circuit currents in your network?

today	in 2 - 5 years
- yes	- yes
- no	- no

7. Please indicate the voltage level were the limitation is needed.
   - nominal (rated) voltage .... kV (today)
   - nominal (rated) voltage .... kV (in 2 - 5 years)

8. Please indicate the max. total short circuit current (I_k” (rms, sym.)) for this voltage level (if not applicable for your system together with voltage level).

today	in 2 - 5 years
- 10 ... 20 kA	- 10 ... 20 kA
- 20 ... 31.5 kA	- 20 ... 31.5 kA
- 31.5 ... 40 kA	- 31.5 ... 40 kA
- 40 ... 50 kA	- 40 ... 50 kA
- above 50 kA	- above 50 kA

Appendix B

Modeling and simulation issues

Depending on the technology adopted, different FCLs will influence the system characteristics in significantly different ways during a system fault situation. Beside reduced fault current amplitudes, the phase angle of the fault current, the duration of the fault, and the recovery voltage will change. Simulations of the transient behavior are an accepted approach to support research and development activities and to mitigate risks for technology deployment,. The most comprehensive method for studying the transient behavior of FCLs in power systems is certainly using a fully transient, physics based simulation model of the FCL. However, in some cases it might not be necessary to model all the physical details. Depending on the investigation to be conducted, more simplified models which represent the FCL behavior may be sufficient.

A first attempt to describe this basic transient behavior of an FCL during a current limiting event in a generalized form has been reported in [1]. However, additional parameters such as the phase angle of the follow current and harmonic current distortions caused by some solid state FCLs should also be included [4]. Such behavioral models of FCL devices are likely to be adequate for most protection system studies. If the exact time domain waveform of the fault current, especially during the first half cycle is required, a physics-based high fidelity model has to be employed.

If the interaction between a real relay and a power system with one or more FCLs has to be analyzed it is most advantageous to use a real-time simulator such as the RTDS™ [5]. Figure 17 illustrates such a RTDS simulation test setup. A simple power system model and, in this case, a fully transient model of a resistive type superconducting FCL (SCFCL) was implemented on the RTDS™ [6]. The protection device, in this example a distance relay, receives voltage and current signals from one end of a transmission line T2 and sends trip signals to the breakers on both ends. Without an FCL present in the simulation, the relay trips the breakers properly for faults within 80% of the length of the line. However, if a SCFCL is introduced between the PT location and the line the relay's impedance algorithm miss-interprets the additional impedance of the SCFCL as part of the line impedance.

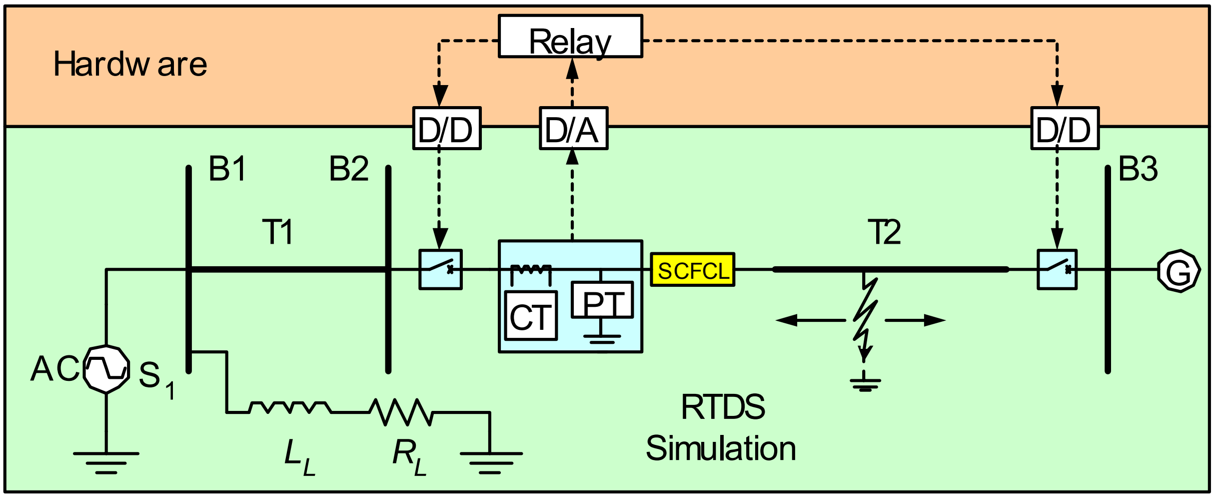

Figure 17 Real-time simulation test setup (from [6]).

The algorithm places the fault outside its protection zone and consequently does not trip the breakers (see Figure 18). If, however, the PT is placed between the FCL and the line the relay is able to properly determine the faulted line impedance in forward direction and trips the breakers appropriately (see Figure 19).

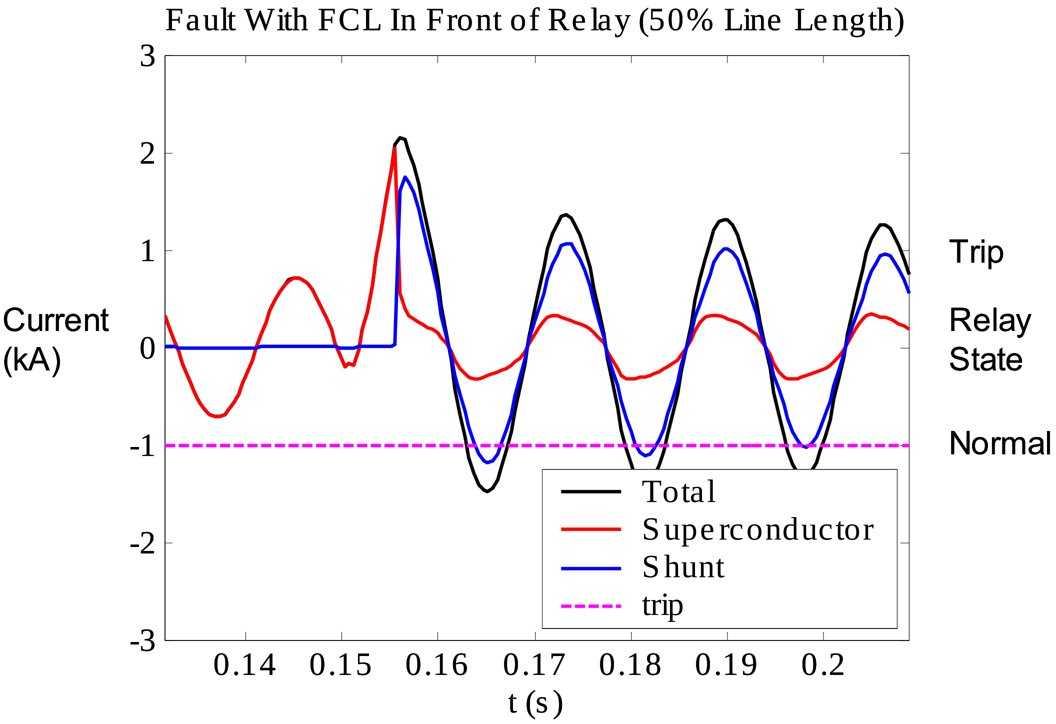

Figure 18 Real-time simulation test, FCL upstream of PTs and CTs (from [4]).

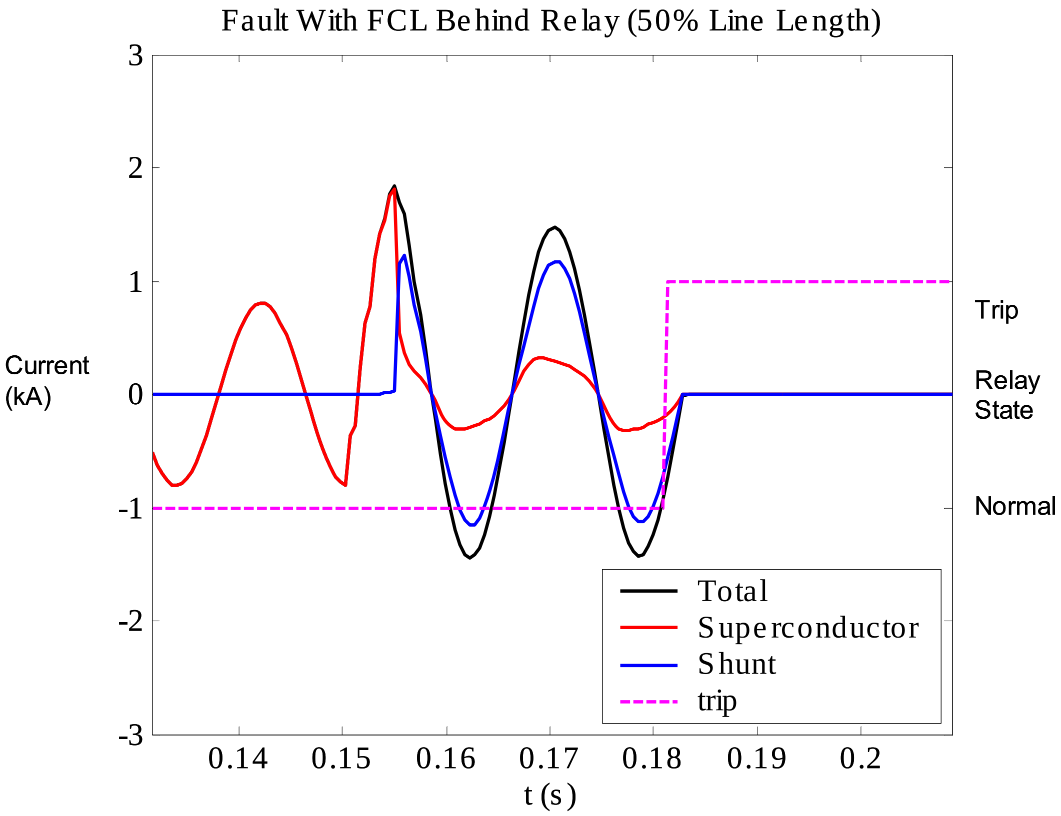

Figure 19 Real-time simulation test, FCL downstream of PTs and CTs (from [4]).

Appendix C

Equivalent circuit approach

Limiting current and limiting resistance should be defined when FCLs are installed in the power system. The equivalent circuit approach is an easy way to study these values [7].

Figure 20 shows an example of a simplified power system, which transmits power from a up-stream system by receiving two feeders. Power source, transformer impedance XT and back impedance XB should be separated if there is another up-stream system. A three line to ground fault (3LG) is assumed to occur at a certain point in the transmission line, where the limiting resistance is R_F.

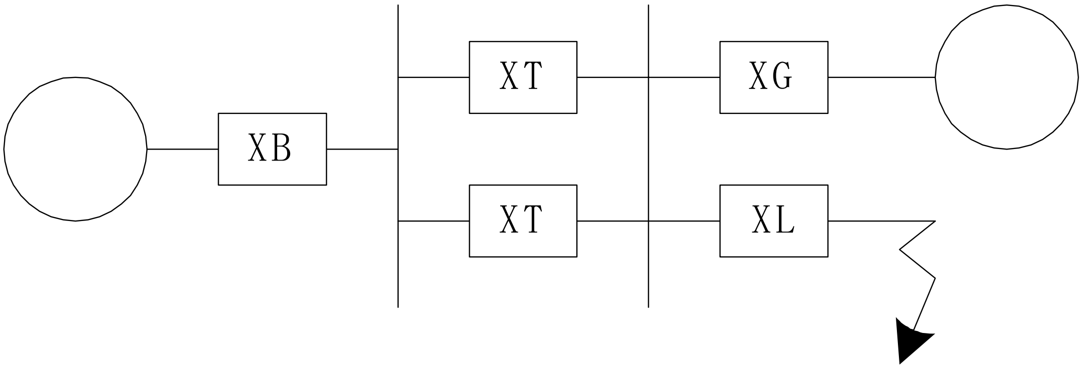

Figure 20 Example power system to study.

The equivalent circuit for the method of symmetrical coordinates is shown in Figure 21. In this example, the maximum fault current (rms value) would flow at the 3LG case. It can be simple because only positive sequence impedance should be considered in this case.

The example case considers that an FCL is installed to reduce higher fault currents than that of an existing circuit breaker capability I_{CB} at line faults. The FCL is installed at the sending end of the transmission line, bus or at the low voltage terminal side of connecting transformer.

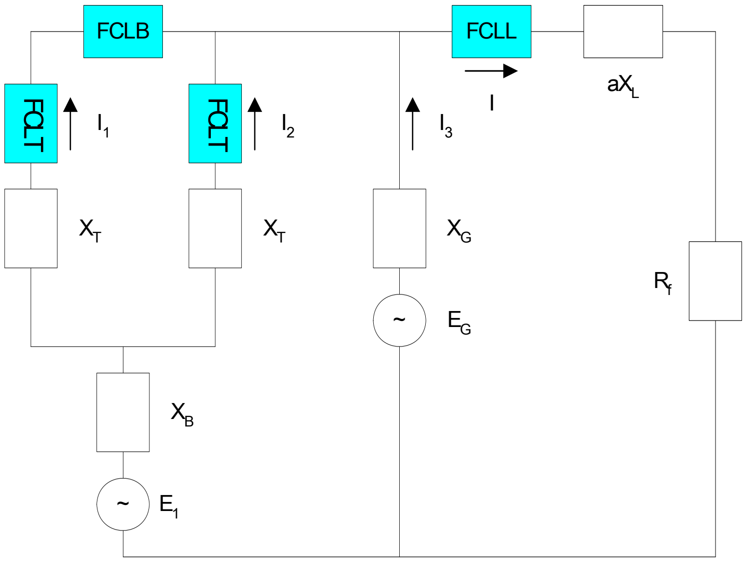

Figure 21 Equivalent circuit of 3 LG line fault case.

1. Limiting current

Operating duties of the FCL should be discussed, which include energized and non-energized cases. The energized case considers the operation of the FCL during the fault. The non-energized case considers the non-operation of the FCL during normal load operation conditions of the system.

Generally, the limiting current can be determined according to the following condition:

Maximum current of normal operation I_n ≤ *Limiting current* I_L ≤ *Current breaking capacity of CB* I_{CB}

2. Limiting resistance

As shown in Figure 22 the CB current I_{CB} in the transmission line could be controlled appropriately so as to be lower than the current breaking capability of the CB and higher than threshold level of power system protecting parameters at the protecting relay activating moment.

The following items should be discussed:

1) Resistance characteristics and thermal characteristics of the FCL.

2) Type, design concept and principle of existing protecting relay system.

3) Operating condition of the power system such as maximum and minimum value of the back impedance.

4) Operating time of protecting relay, which includes the opening time of the CB.

5) Backup protection if the initial protection failed, which includes the type of backup protection, threshold value and operating time.

Considering the permissible current range due to these items, the limited current at FCL activation generated with R ohm of limiting resistance can be estimated using the equivalent circuit shown in Figure 21. The value of limited current should be within the permissible current range.

If the first peak of the fault current has to be suppressed lower than the current breaking capability of the CB, the limiting resistance should be determined assuming 100% transient DC component included in the fault current.

The maximum fault current case has to be investigated to estimate extra system operation such as maximum system back power capacity and parallel feeder operation although the fault current would be lower than the current breaking capability of the CB normally.

The FCL specification includes not only limiting current and limiting resistance as mentioned but also recovering characteristics, maximum limiting current through FCL during FCL operation, TRV, insulation and other items to be discussed.

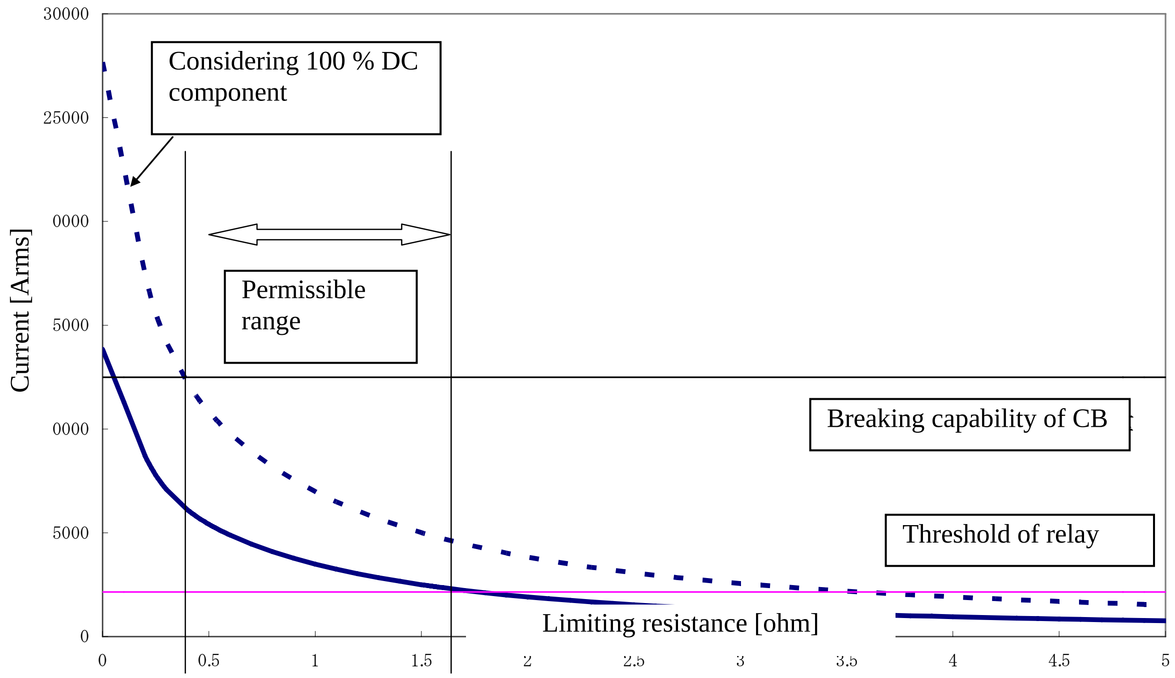

Figure 22 Parameter setting example of limiting resistance.

APPENDIX D

Application of FCL at Medium Voltage (MV)

The following three single line diagrams show typical applications for short-circuit limitation with I_S-limiters and fuses.

I_S-limiters and fuses are FCLs (fault current limiters), which limit and interrupt the short-circuit current in the first quarter of a cycle (no follow current!). Both FCLs (I_S-limiter and fuse) limit the short-circuit current according to the principle of a current-limiting fuse. As it is possible to realise the current-limitation of smaller nominal currents (< 250 A, outgoing feeder) within the first current's rise by using a fuse, for higher nominal currents (> 250 A) such a fuse can not be designed. The limitation of the current would not be done within the first cycle of current.

For these applications (i.e. in the coupling, in the interbus connection or in an incoming feeder) the I_S-limiter will be installed successfully: for the service current a fuse element will be by-passed. Only in case of a short-circuit fault this fuse element will be switched into the current path for limiting the current.

Preferred applications for the I_S-limiter are for high nominal current and fast current limitation as:

- ***interbus connection***
- ***incoming feeder***
- ***in parallel to a reactor***

Due to the small nominal current (I_R < 250 A) fuses will be used only in outgoing feeder (blue protection area, see Figure 23 and Figure 24).

The shown two I_S-limiters in Figure 25 are designed with selectivity, so only that I_S-limiter will operate, which is located close to a fault location.

For a short-circuit fault on the left side of I_S-limiter 1 only I_S-limiter 1 will operate. For a short-circuit fault on the right side of I_S-limiter 2 only I_S-limiter 2 will operate. If the short-circuit fault occurs in the middle section (i.e. between I_S-limiter 1 and I_S-limiter 2), of course both I_S-limiters will operate.

As the limitation and interruption of the short-circuit current will be done in the first quarter of cycle, all applications with the I_S-limiter, which are realised up to now, demonstrated no impact to the existing protection scenario.

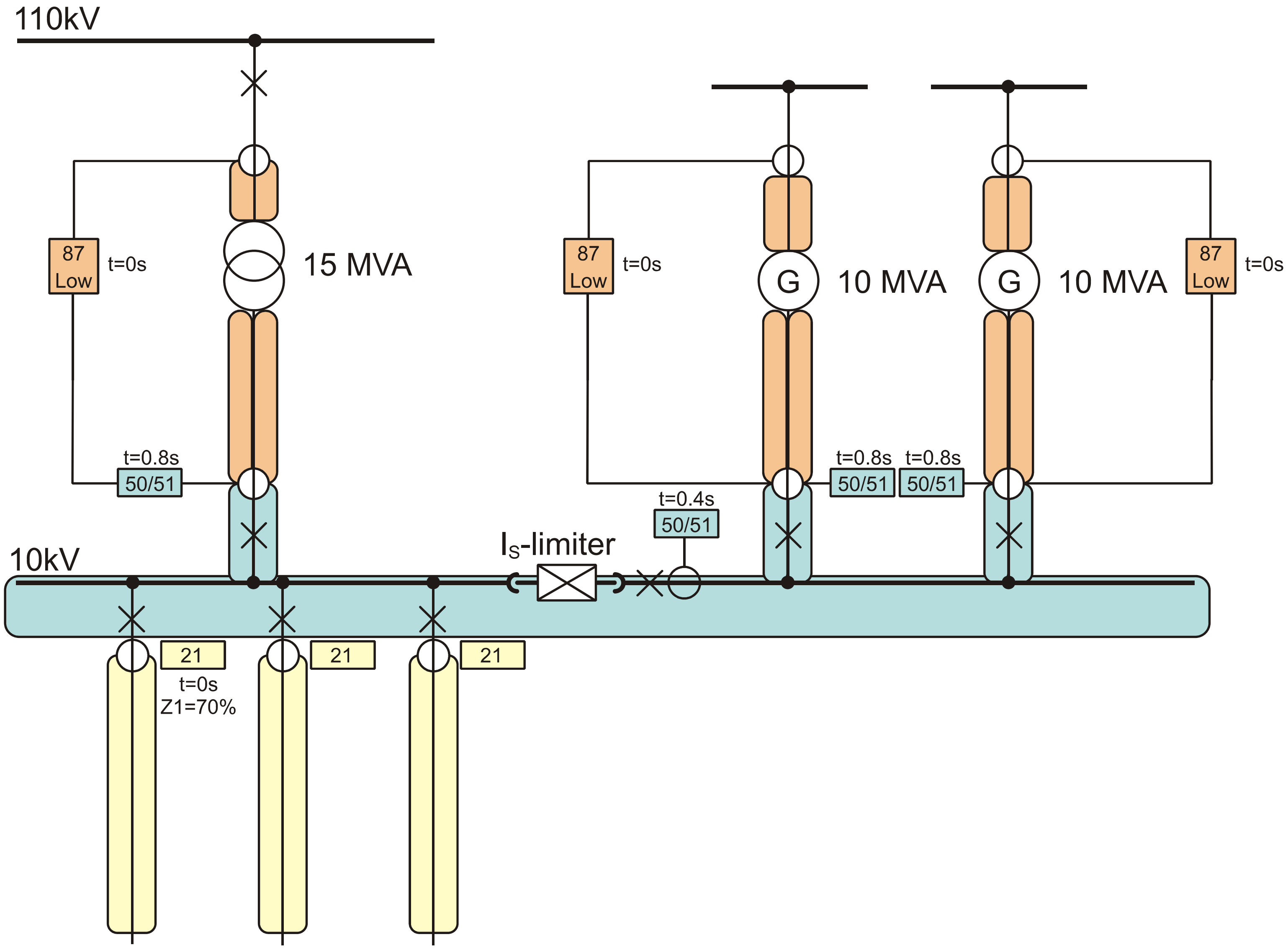

Figure 23 MV application case 1: Is-limiter installed between utility system and IPPs

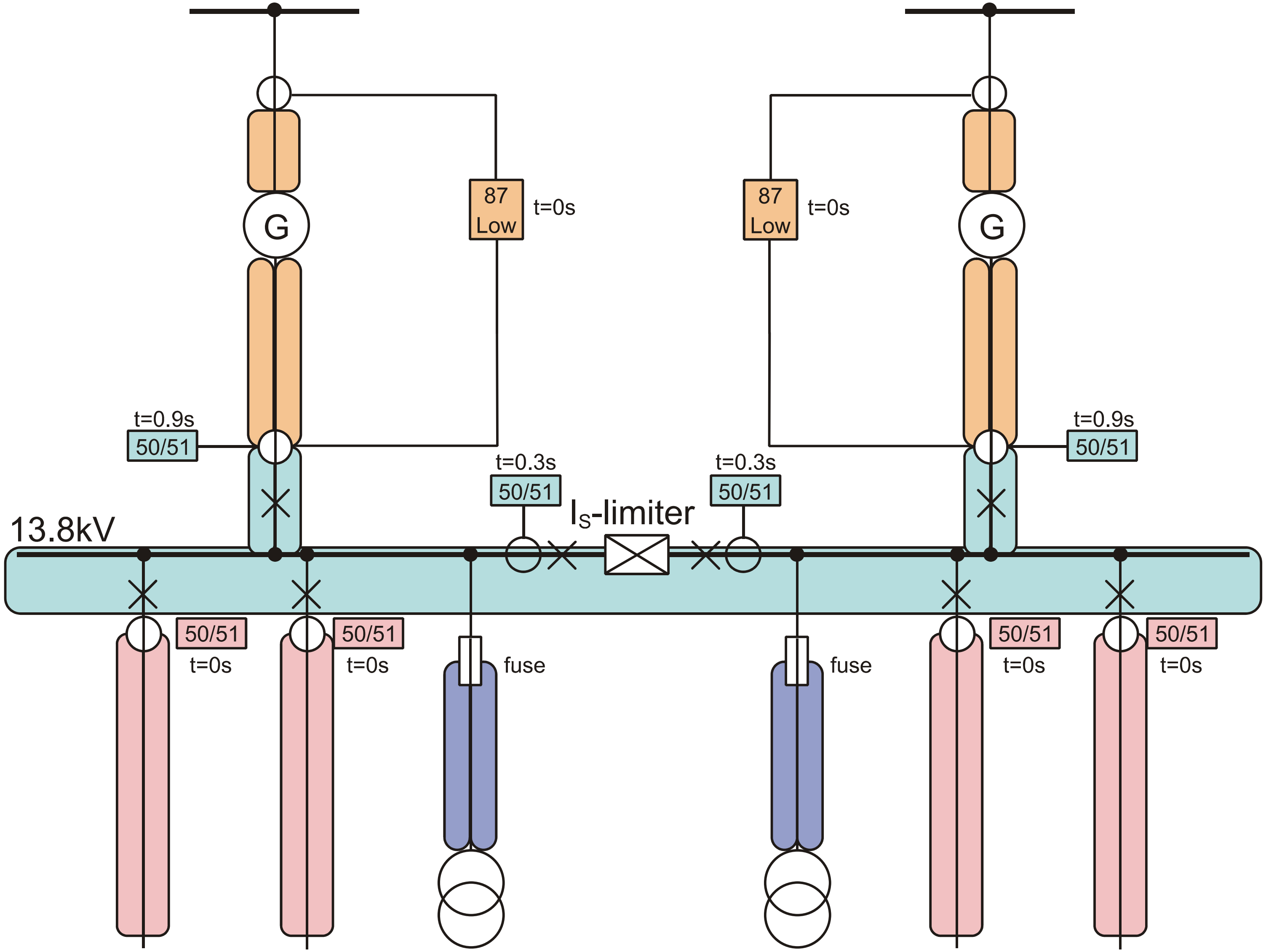

Figure 24 MV application case 2: Is-limiter installed on off-shore platform

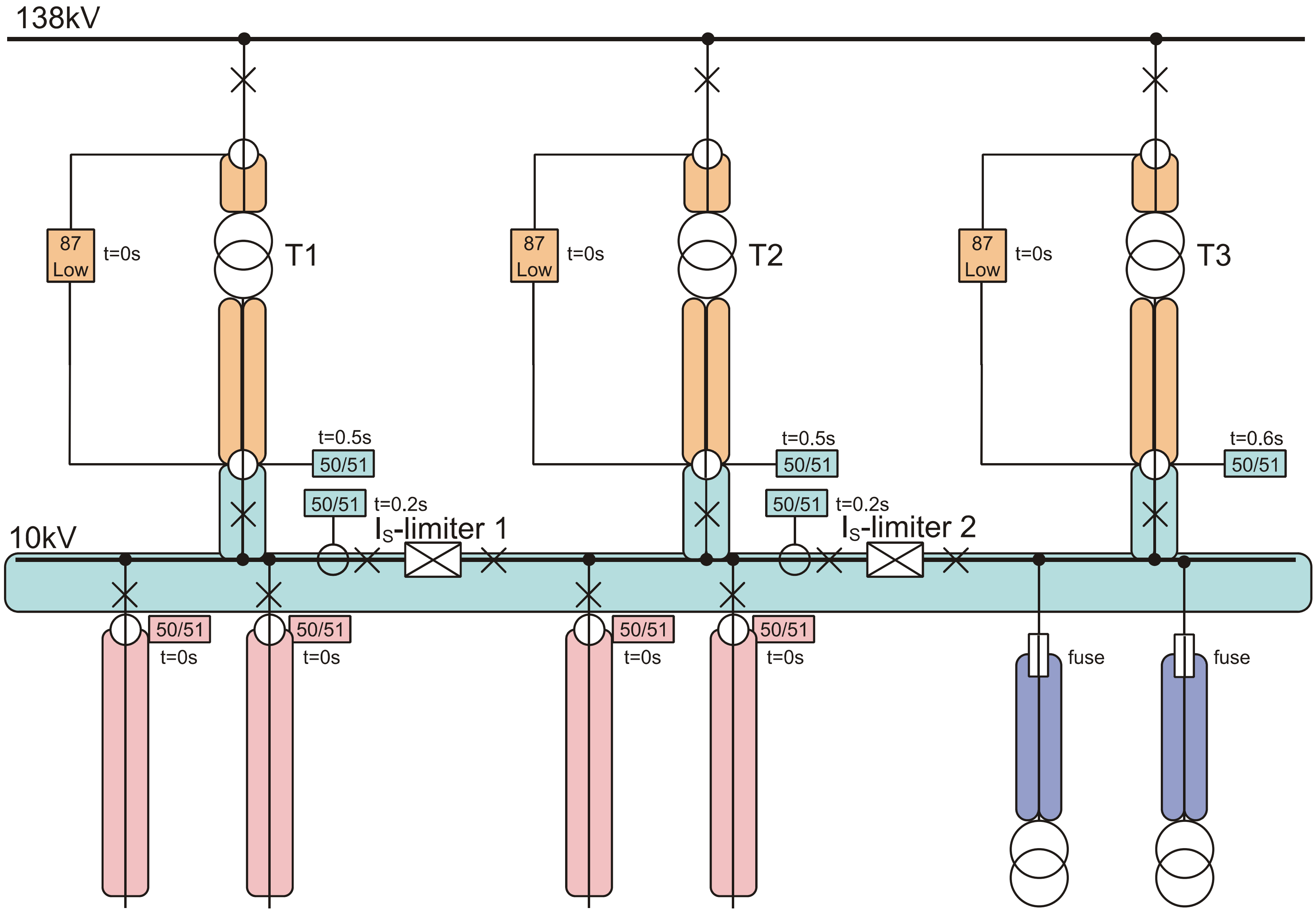

Figure 25 Practical application case 3: Is-limiter installed in an industrial system

Application of FCL at High Voltage (HV)

In recent years, the ever increasing need of short-circuit current limitation in bulk power systems is related to the fact that power systems are worldwide, progressively facing market liberalization, deregulation and need for higher competitiveness. This is related to the free-access to the power grid (or related to the liberty for demanding access to any point of the grid) both for new “IPP” (Independent Power Producers) and ‘non-captive’ consumers.

In this deregulated environment the utilities, responsible for operating the networks, are losing control over the sitting and scheduling of generation growing/expansion.

The connection of IPP to transmission/sub-transmission/distribution networks causes an increase of short-circuit currents not included in previous long-term planning forecasts. A consequence of this development is that at certain points of the networks the short-circuit currents approach or even exceed the withstand strength given by original specification values for short-circuit ratings of substation equipment.

In such framework, the possible use of ‘fault current limiters’ (FCL) is very attractive also if their impact on the protection functions/schemes in electrical systems must be evaluated. Depending on the specific fault current limiting technique and its location, today’s protection concepts may have to be adapted, or revised, to ensure proper coordination and selectivity of network protection.

A relationship between the impact of FCL on protection schemes should be established by taking into account both protection and network specific issues, such as, existing and new protection concepts, protection coordination and selectivity and innovative network configurations.

FCL location at the busbar-tie position

Regarding the framework of “FCL best location investigation”, it is relevant to point out that, independently of the type and characteristics of the FCL devices considered, the performance of any of the protection types described in this report is not affected when the FCL is installed in the middle of the busbar (bus-tie position), as shown in Figure 26. This statement is valid for protection installed in any of the power system equipment directly connected to the referred busbars, such as transmission lines, capacitor banks, shunt reactors, transformers, generator units, etc, having the protection zone bounded by the CT of such equipment.

Therefore, since the goal of such FCL devices is to limit the fault currents flowing through the electrical equipment of the power system, under their withstanding levels (i_{sc} amplitude and/or TRV), once the desired downsizing of the fault currents is achieved, any re-adjustment of settings or modifications in the protection system are not necessary in this mentioned FCL location type ('busbar-tie position') [8].

Also, this FCL position at the substation busbar yields, in all cases, better voltage regulation and minimum resistive losses, regarding other possible FCL locations (substation incoming or outgoing feeders).

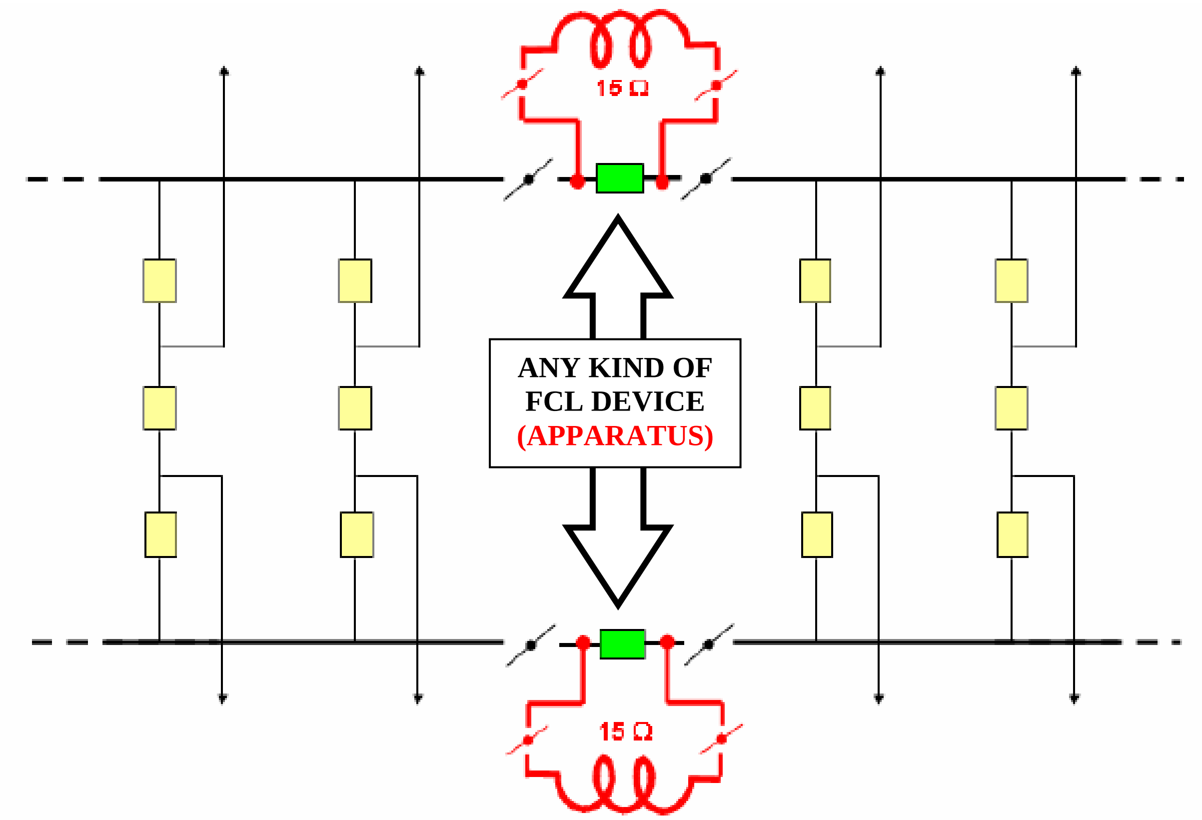

Figure 26 FCL devices (to be) installed in the 'middle' of busbar (bus-tie position) [8]

Appendix E

Types of FCLs and their characteristics

The different types of FCLs and possible classification criteria like voltage levels, superconducting or non-superconducting are shown in Table 12. Further FCL characteristics like trigger mechanism, current interruption, follow current control and ability to reset are shown in this table too.

Groups	FCL's	Self-triggered or external triggered	With or without current interruption	Follow current control	Resettable or non-resettable
		Self-triggered? Yes or No?	With current interruption? Yes or No?	Active or passive?	Resettable? Yes or No?
Medium-Voltage Networks Rated Voltage: 1 kV ..... 36 kV (40.5 kV)	High-Voltage Current Limiting Fuses	Y	Y	(N/A)	N
	Pyrotechnic Fault Current Limiters (Is-Limiter)	N	Y	(N/A)	N
	Resonance Links	(Y / N) : depending on the bypass circuit	N	Active	Y
High-Voltage Networks Rated Voltage: > 36 kV (40.5 kV)	Resonance Links	(Y / N) : depending on the bypass circuit	N	Active	N
	Thyristor Controlled Series Compensators with Fault Current Limitation	N	N	Active	Y
Novel Approaches: Superconducting Fault Current Limiters	Resistive type	Y	N	Passive	Y
	Shielded iron Core type	Y	N	Active	Y
	Saturated cron core type	Y	N	Active	Y
	“Current Controller”	Y	(Y / N) depending on the layout of the device	Active	Y
Novel Approaches	Fault Current Limiters Based on PTC-Resistors	Y	Y	Passive	Y number of operation limited
	Liquid Metal Fault Current Limiters	Y	N	Passive	Y
	Solid-State Fault Current Limiters	N	(Y / N) depending on the layout of the device	Active	Y
	Fault Current Limiters Using Electromagnetic Forces	N	Y	Active	Y
	Hybrid Fault Current Limiters	N	Y	Active	Y

Table 12 Classification of active (conditional impedance) FCLs

FCL technical items to be discussed

Table 13 shows the categorized items about FCL technology, which should be discussed if FCL products are standardized. No standards are available at present because the application of FCLs in power system is not so common world wide. FCLs have unique technologies and characteristics different from other devices such as circuit breakers or shunt reactors, and there are various kinds of topologies so that discussing their technical items is important. As the first step of discussion, possible items and keywords are listed in the following table as reference. Further discussion of each item would be necessary as the next step, when the application of FCL will become more common for protecting electrical devices in power systems.

	scope of application
	ambient conditions
Rating	voltage
	withstand voltage, insulation level
	(normal) current
	frequency
	limiting current
	transient recovery voltage
	making current
	short-time withstand current
	duration of limiting operation
	pressure of compressed gas supply for operation
	control voltage
	standard operating duty
	duration of short-circuit
	impedance

Construction, Performance	structure, construction, constitution
	mechanical strength
	internal constitution
	operation and control device
	temperature rise
	insulating strength
	mechanical endurance
	cooling system
	terminal symbol
	short-circuit strength
	current limiting characteristics
	switching voltage
Type test	structural inspection
	closing and opening test
	temperature-rise test
	power-frequency withstand voltage test
	impulse withstand voltage test
	withstand voltage of control circuit
	short-time withstand current test
	limiting test
	mechanical endurance test
	measurement of resistance
	measurement of impedance
	measurement of loss
	induced voltage test
	noise measurement
	fusion characteristics test
	permissible time-current characteristics
Acceptance test	structural inspection
	closing and opening test
	measurement of resistance
	power-frequency withstand voltage test

Table 13 FCL technical items