ANALITICAL MODEL OF CURRENT LIMITER

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Discussing the state and types of current limitation in medium and high voltage ranges show the limits and drawbacks of today's current limiting techniques. Focusing on up-to-date research projects in the field, the major part of this paper explains various kinds of current limitation by means of super conducting materials. The two major principles, resistive and inductive limiters, are introduced as well as hybrid approaches. Unsolved problems using high temperature superconductors HTSC for current limiting devices are discussed.

Keywords: current limitation, super-conductive materials, hybrid approaches, voltage, resistive limiters, inductive limiters.
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1. INTRODUCTION

The consequences of inevitable fault currents i_F in electric power networks, more than an order of magnitude higher than the nominal current, usually means severe stress for the affected apparatus such as

- thermal stress proportional to $\int i_F * dt$
- mechanical stress proportional to $\int i_F^2 * dt^2$
- damage due to power dissipation at the fault location

Continuously increasing electric power production, distributed with high density meshes, may drive power networks to the limits of their short circuit current capability. Novel apparatus such as superconducting generators, motors, and power lines and the increasing demand on power quality makes effective short circuit current limitation desirable [1].

Many investigations have been carried out so far in the field of current limitation devices (CLD's), but still only few systems are commercially available, especially in medium voltage range. However, these systems either lack on limiting performance or they do not cover the entire power range needed. [2] Although there are continuous research projects in the field of CLD development. For the time being none of these approaches led to commercially acceptable systems [3]. Even though there always has been the desire for current limiters [4], especially the discovery of the so called high temperature superconductors (HTSC) with their nonlinear u-i characteristic available at the temperature of liquid nitrogen (T ≥ 77 K) in 1986 started new efforts to develop CLD's [5].

This paper starts with the basic considerations on fault current limiters, explains why solutions used for low voltage range cannot be scaled to medium voltage and describes some of the various forms of novel approaches for CLD's, mainly those with HTSC. Not covered in this paper are single phase to ground faults in reactor earthed networks with reactors for short circuit current limitation. This technique is well known and widely used. Also not addressed are attempts for novel current limiting systems for ungrounded power distribution systems [6]

2. SHORT CIRCUIT CURRENT LIMITATION

2.1. Basics

Figure 1 shows a simple equivalent circuit for discussing the difficulties at short circuit current limitation in electric power networks. Independent of the load flow prior to the fault, the short circuit current (SCC) i_S increases with a certain rate of rise depending on the circuit parameters (U_0 and L_S = R_S+i_F) and the phase angle of fault.

This leads to the current wave form i_1 in Figure 2 when no limiting action takes place (prospective SCC). The simplest way to limit this current would be to choose an appropriate high source impedance L_S. This is indeed the state of the art technique at medium and high voltage levels. But as this effects nominal load flow as well it can’t be the reasonable technical solution for the future. Without extra limitation a conventional circuit breaker CB breaks the current at t_3.

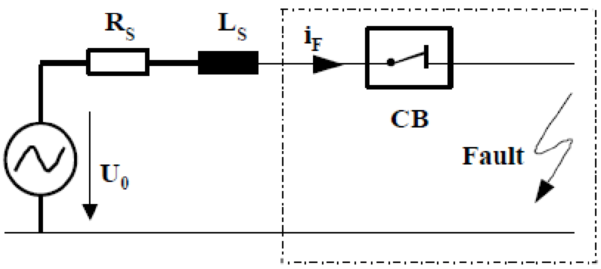

Fig. 1. General equivalent short circuit diagram (framed part is used in subsequent figures).

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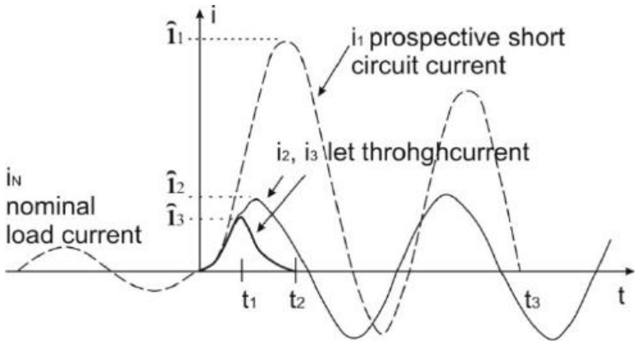


Fig. 2. Typical current waveforms at fault conditions.

To limit the first current peak î1 the limiting device must react within the time interval t_1 and restrict the rise of current $\frac{di}{dt}$ at least to zero (or below) at this point (i_2, i_3). This can only be done by forcing the voltage drop at the circuit's inductive reactance L_S to become zero $u_L = L_S \frac{di}{dt} = 0$, which means the need of inserting an appropriate high voltage drop. Such an action (changing the circuit parameters) can only be provided by a non linear element and leads to the sketched let through currents, depending upon weather the current is only limited (i_2) or also switched off (i_3) at t_2. Circuit breakers that insert the voltage drop of a burning arc are the preferred devices at least at low voltage range. It shall be noticed that to be efficient, the reacting time of a current limiting device (CLD) must be in the range of t_1 < 1...1,5 ms for power frequency f_N = 60 or 50 Hz.

For better understanding of the problems the following two sections describe the usual way of current limitation in the low voltage (LV) range (household and industry applications) and the reasons why this simple but effective technique fails at medium voltage (MV) range. Commercial solutions for current limitation in MV will also be compared.

2.2. Low voltage range

From the equivalent circuit in Figure 1 it easily can be seen that an inserted voltage drop in the order of magnitude of the source voltage U0 will be sufficient to force the inductive voltage drop u_L to be zero or even negative. When opening the contacts of a circuit breaker the voltage drop of a free burning arc between the opening contact gap would only be several 10 Volts. The state of the art is to increase the arc's power dissipation by cooling it and splitting the arc into series connected subsections (therefore gaining several cathode drops in series). This increases the overall voltage drop of LV current limiting switchgear significantly. Suitable devices are produced in large numbers and are well known as:

- Fuses:

intensive cooling of the melting wire and finally the arc by the surrounding quartz sand, as well as splitting the arc into sub-sections,

- Circuit breakers:

splitting the arc by metal baffle plates.

Effective current limitation at prospective currents in the range of up to 100 kA limited to several kA can be achieved by those well proven techniques.

When the line voltage increases over 1 kV it gets more and more difficult to design circuit breakers with current limiting capability. Only high voltage heavy duty fuses with nominal currents of several 100 A can be built for commercial use.

2.3. Medium voltage range

The principles of current limitation stated above are basically the same at medium voltage (MV). Typically in MV networks the ratio $\frac{R_S}{L_S}$ is less than in LV. As a consequence the inductance L_S is typically higher in MV networks assuming the same ratio of $\frac{\hat{\imath}_F}{\hat{\imath}_N}$. Therefore the voltage drop that has to be provided by the limiting device has to be over proportionally higher compared to that of LV systems.

Some few research projects indeed introduce the switching arc voltage in special designed circuit breakers for current limitation at MV, but the success is rather poor (12 kV/1 kA) [7]. As the number of sub arcs increase with the nominal voltage, it gets more and more complicated to achieve the necessary sub divisions from the constructive point of view.

If the switch itself cannot produce enough voltage drop by the means of an arc one might think of transfer the current to an appropriate limiting impedance Z_L (Figure 3). Therefore the transfer switch TS has to commutate the fault current iF within the time interval t_1 (comp. Figure 2) to such an impedance and withstand the subsequent transient recovery voltage (TRV).

The value Z_L at power frequency has to be high enough to limit the current effective and can easily be calculated to 1...20 Ω minimum for typical MV power ratings. From the 3 basic linear electrical elements

- Resistor
- Inductance
- Capacitor

only a capacitor would be sufficient. Because a not pre-charged capacitor is a short circuit at the time of commutating, the switch TS could perform that task even at MV.

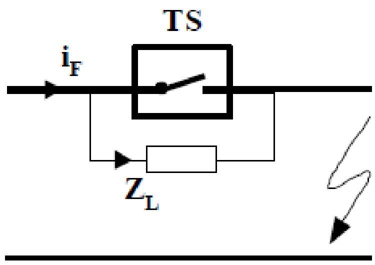


Fig. 3. Inserting a limiting impedance in line at fault occurrence.

The rate of rise of the recovery voltage across the opening switch would be limited by the capacitor to acceptable values. But unfortunately this would require capacitors of several mF and they would be commercially unacceptable.

The other two possibilities left, resistive or inductive impedances therefore have to have a non linear characteristic to provide a sufficient time delay for the switch to recover.

A solution without a switch parallel to the impedance needs a non linearity of even higher order. Most of the novel approaches on CLD's using HTSC follow this principle.

Current limiting devices using one or both of these two principles might be called **active** (changing the circuits electrical parameters after fault detection) in contrast to **passive** limiting measures where the limitation is performed by simply increasing the source impedance Z_S as stated in 2.1.

Table 1 shows the possibilities for current limitation commercially used by various utilities. Besides topologic attempts, which are long term solutions that highly effect grid layout, today two solutions are in use which are commercially acceptable:

- Increasing the grid impedance by transformer design or limiter coils
- Installation of high voltage fuses or I_S-limiters

Novel approaches for current limitation in MV are all settled in the active or "switching" category, meaning they all use one or both of the two main possibilities:
inserting a resistive or inductive impedance short after fault occurrence.

Table 1. Overview on major current limiting measures in medium voltage range including novel concepts

Passive Increase of impedance at nominal and fault conditions	**Active** Small impedance at nominal load fast increase of impedance at fault	
Splitting into sub grids	High voltage fuses (< 1 kA, < 36 kV)	
Introducing a higher voltage range	I_S-limiter (< 4 kA, < 36 kV)	
Splitting of bus bars	**novel concepts**	Semiconductors
Transformers with high stray impedance		HTSC
Current limiting air coils		Hybrid systems

Picking out the most powerful current limiting device commercially available, the IS-limiter shall be described briefly in the following chapter.

3. NOVEL APPROACHES

3.1. Superconducting current limiters

Since superconducting materials have a highly non linear behaviour they are principally good candidates to build CLD's. Investigating low temperature superconductors (LTSC) operating at the temperature of liquid helium (4 K) as well as high temperature superconductors (HTSC) with critical temperatures around the boiling point of nitrogen (77 K) many designs for superconducting CLD's have been presented. Currently there are around 20 projects running worldwide in this field [5].

Whereas CLD's using LTSC are still under development, most efforts are made to build HTSC CLD's. The two most important HTSC materials are

- Bismut-Strontium-Calcium-Copper-Oxide (B2212 and B2223) mostly for filaments and
- Yttrium-Barium-Copper-Oxide (YBCO123) mostly for thin film techniques.

Taking advantage of the quench of an SC, the high increase of resistivity when exceeding one or more of the critical parameters such as

- current density j_C,
- temperature T_C or
- magnetic flux density B_C

(Figure 4) lead to the two principles pointed out in chapter 2.3:

- Resistive current limiters where the SC is in line with the source and load
- Inductive current limiters where the limiting impedance is magnetically coupled to the line by means of iron cores.

But there are also concepts not using the SC's quench but it's negligible resistivity below j_C, T_C and B_C. All those will be described in the following including selected examples of ongoing projects.

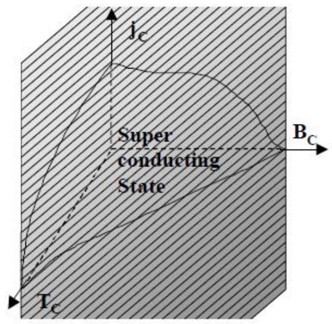


Fig. 4. Typical 3D-Diagram of the critical parameters of a SC.

3.1.1 Resistive current limiter

Using the SC in line with the source leads to the resistive CLD where a principal schematic diagram is given in Figure 5. A cryostat holds the SC resistor R_{SC} which is connected straight to the power line by current leads, specially designed for minimal heat transfer. The load switch LS in series is necessary to save the R_{SC} from undue high power loss under fault after tripping and allows a sufficiently short recovery time (1...1,5 s). A resistive or inductive shunt Z_{Sh} might be added for thermal relief as well as for upholding a minimum current flow.

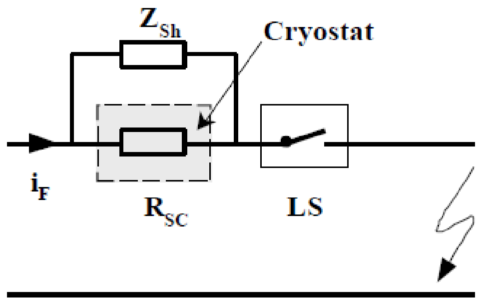


Fig. 5. Schematic diagram of a resistive SC-limiter.

When the fault current reaches a value equivalent to j_C, quenching of the SC causes a rise of the resistance R_{SC} and therefore current limitation. With RSC increasing, power dissipation heats up the SC and leads to RSC_WARM, the resistance of the heated SC (approx. room temperature). Values of the resistivity ρ_{SC_WARM} for common SC materials are in the range of 10-4... 10-3 Ωcm which results in long, thin SC designs to achieve the necessary resistance in the orders of several Ω for effective limitation in MV. This is actually the most important problem to solve when designing HTSC resistive CLD's. The heating is not uniform along the entire length because of inhomogeneous regions within the SC material. This results in so called "hot spots" which destroy the material locally. So the SC has to be shunted by thin conducting films (e.g. Ag or Au) to smooth the temperature distribution in length. These shunt films also reduce the heated up resistivity and lead to even longer stripes.

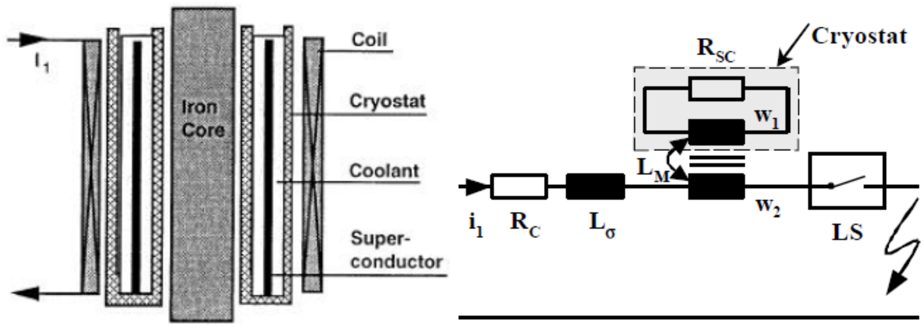
Another attempt to overcome the "hot spot" problem is to spread thin films (several μm thick) of SC on non conductive substrates. A research project from Germany [9] works with this technique to develop a resistive SC limiter built up of meander shaped thin film stripes connected in parallel. Today's switching capabilities are still rather poor in the range of several kVA. But since this design allows for a very compact limiter with minimal weight the project is still carried on.

Even though most of the SC limiter projects today are on HTSC there are still some in progress with LTSC. Both, a British project (63 kV/1,25 kA) [10] as well asone from Japan (6,6 kV/1 kA) [11] use low inductive winded coils. The main problem with LTSC is the unwanted heat transfer into the cryostat by the current leads. Therefore the current leads are built of HTSC bulk tubes with a comparatively low thermal conductivity.

The heat transfer throughout the connectors of a resistive SC limiter is an inherent problem of that principle and therefore the inductive limiter (and variants) is a potential alternative to the former.

3.1.2. Inductive current limiter

When speaking of inductive SC limiters, basically the shielded iron core type is meant. Figure 6 shows the build-up and the electrical equivalent circuit, which is in principal the one of an short circuited transformer. In normal operation, the overall impedance of the device consists of the DC resistance and the stray inductance of both, the primary coil and the SC coil. One can say, the SC coil shields the iron core as the axial magnetic field in such a "long" SC coil is zero due to shielding currents flowing on the outer surface of the SC coil. In the case of a fault, the SC quenches and the value R_{SC} is transferred to the primary side by the square of the transformer ratio w^2, with $w = w_2/w_1$. The inductive SC limiter is thus actually a resistive type, but due to the inductive coupling it's known as the inductive type.



a) b)

Fig. 6. a) Concept of an inductive SC-limiter (shielded iron core) /11/; b) schematic of the equivalent circuit.

Looking closer to the actual build-up one can see, that the secondary coil consists of only one winding: a staple of rings of SC bulk material (typ.: BSCCO). Only these rings are kept at 77 K by the liquid nitrogen in the cryostat. Both other main parts, the iron core and the primary copper winding are at room temperature. This is actually one of the great advantages of this concept, because there are no current leads to the SC and therefore minimal thermal losses as stated above. The second advantage of the transformer principle is the possibility of adjusting the necessary SC coil resistance after quenching by means of the transformer ratio w. Typically w_1 is chosen to be 1 since it's easier to built low resistive-high current SC rings than long stripes. Also the "hot spot" problem is easier to overcome with this design. Again, finally a load switch LS has to interrupt the current to avoid overheating of the SC.

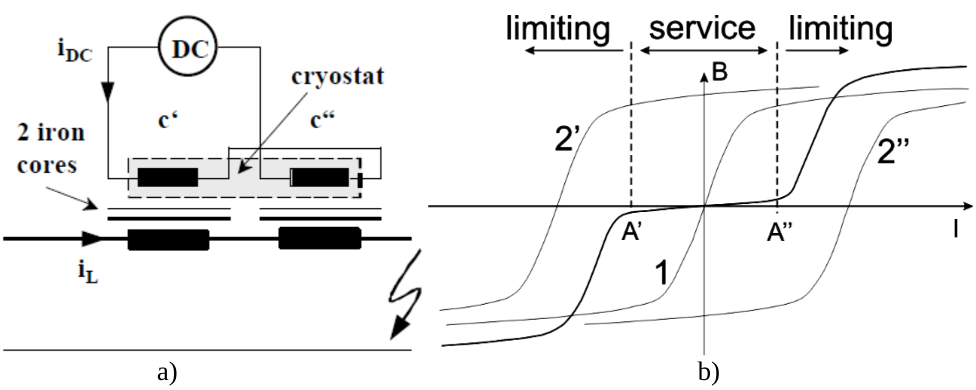
The main disadvantage, beside it can't be used for DC applications, are the size and weight in the range of a transformer equivalent to the nominal power of the CLD. Also the normal conducting primary coil leads to unwanted power dissipation trough normal operation. Nevertheless this system led to prototypes of highest power ratings tested so far. In Switzerland field tests of an 1,2 MVA limiter have successfully been performed at a power station [12]. This CLD consists of 3 limiter coils of approx. 2 m height with SC rings 38 cm in diameter.

Besides this two basics approaches there are a variety of other concepts introducing SC for CLD's [13]. Oneof them where the SC stays super conducting during fault conditions shall be described now.

3.1.3. Transduction limiter

The principle of pre-magnetised iron cores can be employed to build a CLD. The principle is old, but with SC coils power losses in the bias coils can be reduced drastically and therefore there are still ongoing projects using the transduction [14].

In Figure 7 **a** the principal circuit diagram of a DC biased CLD is drawn. There are two iron cores with coils, one for each current direction of the AC load current i_L. The DC SC coils c_1 and c_2 keep the iron cores at a certain point of saturation and therefore minimize the overall inductivity of the device. Figure 7 **b** clarifies this by showing the magnetic characteristics of the primary coils without (1) and with DC bias (2', 2") as well as the resulting curve (3). If i_L reaches values equivalent to points A' or A" the inductance rises sharply and the current is limited by the inductive voltage drop.



a) b)

Fig. 7. a) schematic circuit; b) magnetic characteristic of the DC biased CLD.

The advantage of the concept is the use of DC instead of AC for the superconductor. This avoids the AC losses, which are mostly eddy current losses within the SC material. Furthermore the SC stays superconducting all the time which means there are no problems with "hot spots" caused by non-uniform power dissipation during quenching. On the other hand the size of such a device has to be approx. twice the size of an equivalent transformer and this is indeed a major disadvantage.

Not only superconductors with their demand on cooling equipment besides the still unsolved material problems can be used to design fault current limiters. The next section introduces one of the present projects for CLD's without SC.

The mathematical model of the device as a power system element is based on the equations of magnetic coupled circuits:

$$u_1 = R_{11}i_1 + L_{11}\frac{di_1}{dt} + (L_{21} - L_{2'1})\frac{di_2}{dt} + L_{11'}\frac{di_1}{dt}$$

$$(L_{12} - L_{12'})\frac{di_1}{dt} + R_{22}i_2 + (L_{22} - 2L_{2'2} + L_{2'2'})\frac{di_2}{dt} + R_2 i_2 + L_2\frac{di_2}{dt} +$$

$$+(L_{21'} - L_{1'2'})\frac{di_1}{dt} = 0$$

$$L_{12'}\frac{di_1}{dt} + (L_{22'} - L_{2'1})\frac{di_2}{dt} + L_{11}\frac{di_1}{dt} + u_s = 0$$

where u_1 is the primary terminal voltage; i_i, R_{ii} and L_{ii} are the current, resistance and inductance of the coil W_i (i = 1, 1', 2, 2'); R_i and L_i is the resistance and inductance of the load connected to the secondary coil W_i (i = 2, 2'); L_{ij} is the mutual inductance of the coils W_i and W_j. Because the sections W_2 and $W_{2'}$ are electrically connected, we put $i_2 = i_2'$. The voltage drop us across the superconducting switching element depends on the current and temperature. A frequently used approximation for the Current and voltage characteristic waveforms at short circuit current interruption is:

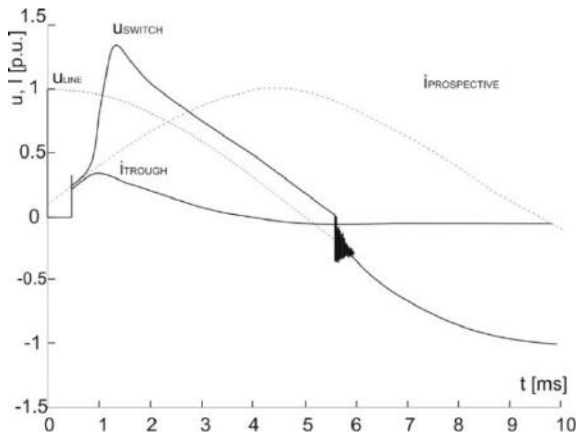


Fig. 8. Current and voltage waveforms at short circuit current interruption with a hybrid current limiter obtained from a computer simulation.

As one can see from the figure 8 above, a short reaction time of the system is very important. A special actuator system allows high acceleration of the moving contact in the nominal load path. Energy storage for that drive is kept low due to a novel design of the mechanical contact area. First tests on an experimental set-up of such a contact system were already performed and satisfied the expectations. A second redesigned model is in process of development to verify the requirements for nominal current ranges up to several kA.

4. CONCLUDING REMARKS

Because it's technical impossible to employ the principle of low voltage current limiting techniques for medium voltage levels many projects have been founded worldwide to develop current limiters for MV. Most of them rely on super conducting materials, both HTSC and LTSC because they have a highly nonlinear electric characteristic when coming out of the superconducting state.

For the time being prototypes in the power range of 1 MVA (HTSC) and 100 VA (LTSC) have been tested successfully. But nevertheless there are many problems to be solved before commercial solutions will be in sight. Material problems as well as costs of the SC CLD's prevent economical attractive apparatus to be built. Even if the majority of the CLD projects are in the field of superconductors, concepts without SC might also be attractive.

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