Fault current limiters and fault current switches based on wide HTS tapes: low cryo-consumption, new applications

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Abstract. When the fault current limiter yields influential response within 0.1 milliseconds, it demonstrates ultra-fast switching behaviour that is significantly faster than the response of the best mechanical and superconducting devices. Such ultra-fast response was demonstrated in recently developed superconducting fault current limiters (SFCLs) of inductive type. Secondary coil of the limiter was constructed from a set of closed rings made out of 40 mm wide YBCO coated conductor that was capable of nucleating wide normal zone in the beginning of quench process. Due to reduction of heat capacity and avoiding internal and external shunts, the ultra-fast switching behaviour with characteristic times of 50-100 microseconds was achieved. The ultra-fast performance results in a suppression of energy absorbed in the device during transient/quenching process as well as in low power dissipation after quenching of the superconducting element. This allows to maintain a very low power dissipation in the limiting modus duration which may be extended therefore to hours. Drastic reduction (by a factor of 10-50 in comparison with conventional types of SFCLs) of cryo-consumption was experimentally demonstrated at both normal operating modus and limiting (quenched) modus. Different ways for implementation of ultra-fast switching performance in fault current limiters are considered and discussed.

1. Introduction
Viability of HTS devices in electrical engineering is mainly determined by their cryo-consumption. Integral losses of HTS based fault current limiters (FCLs) are analysed as a function of “critical” time-period during which the transport current approaches the critical current or even exceeds this value. The normal zone propagation from the generated hotspot in the quenched HTS-SFCL device decides the peak temperature and current decay. A proper estimation of speed of quench (slow quench or quick quench) is desirable by suitable electro-thermal modelling and proper design of active/passive protection provided by the shunt circuits. It is equally important to provide a safe and quick venting path to the copious amounts of vapours coming from the fast boiling of liquid cryogen during quenching.
This way the HTS based electrical devices with low cryo-consumption is a reality to realize a Superconducting Power Grid in the near future.
In this paper, we demonstrate a practical example how the cryo-consumption can be drastically improved in a current conditioning device, that we call a Superconducting Fast Power Switch (SFPS), which can replace conventional SFCL with larger cryo-consumption.
2. Background

Simple limitation of electrical current due to transition of the superconductor to normal conductor is used as resistive fault current limiter. This type of device is with a rather high cryo-consumption because largest cryo losses in the current feedthroughs where about 100 W of cooling power is needed to transport 1 kA current. In other words, cryo consumption of 2 kA device is defined by need of at least 100 liters of liquid nitrogen per day to be used only for compensation of the heat penetrating through the current leads.

Moreover, to implement directly the initial idea of superconductor-metal transition (i.e. quench) turns out to be not so trivial. This is because of additional complexity introduced by inhomogeneous quenching of long tape or wire. “Hot spots” [1] that appear in the beginning of quench propagation lead to high local concentration of energy dissipation in one or several spots. This happens significantly before reaching the current limitation effect and results in burning out of the superconducting tape.

To protect the tape, a metallic shunt layer on the top of the superconducting tape was developed [2, 3]. In this case the hot spot spreads faster because of improved heat conduction and the shunt layer with typical thickness of 10-30 µm plays a role of additional heat reservoir reducing the speed of temperature ramp.

The shunt makes negative impact to the current limiting performance leading to weaker limitation effect because the shunt is always a bypath for the current. Secondly, the heat accumulated in the shunt during quench event has to be released in the recovery stage after the quench [4]. This may prolong the recovery time, sometimes to minutes.

An attempt to split heat dissipation in shunt and HTS tape (i.e. to build an external shunt) was performed in [5]. In this design, the non-shunted HTS tape is periodically linked each e.g. 5 cm over its tape length to an external shunt tape. The links (or interconnectors) are provided in a form of small electrical bridges that are placed periodically along the tape length. If the distance between bridges is less than 2-3 widths of the tape such way of shunting seems to be sufficient to protect the tape against burning out of “hot-spot” areas where energy dissipation is basically suppressed due to the “bridge-linked” shunt.

To avoid cryo losses caused by feedthroughs introducing main current into the cryo vessel an inductive type of superconducting fault current limiter (iSFCL) was suggested [6-10]. Inductive coupling through a common part of magnetic flux between the primary coil and the secondary superconducting short circuited coil allows to very efficient heat insulation. In the present design (see example in Fig. 1), the short-circuited rings based on HTS 40mm-wide tapes are assembled in a way that all of them are linked with substantially the same magnetic flux. In the unfaulted condition all rings together avoid penetration of flux in their interiors. During the initiation of fault, when the induced current in any ring exceeds the critical value that ring quenches and this causes quench of other rings due “cascading” effect. Such behaviour results in strong jump of electrical impedance in the primary resulting in current limiting action (see Fig. 1 b, c).

![Figure 1. iSFCL based on concentric HTS rings. a- basic arrangement, b – equivalent electric scheme, c – V-I curve in case of “avalanche” quench.](image-url)
Another important source of cryo loss in iSFCLs is the shunt or external shunt [3-5] that absorbs huge Joule heat during quench event. On the first hand, this limits duration of current limitation cycle to 100-500 ms (at higher durations the shunt may melt). On the second hand, the entire iSFCL by quench exhibits impedance that by a half is inductive and by other half is resistive. This means that a lot of limited power will be dissipated in the cryostat causing a very high cryo loss during quench. As an example, in 40 MVA iSFCL a quench with duration of 500 ms will result in the dissipated energy of ~20 MJ which corresponds to about 125 L of liquid nitrogen.

3. Superconducting Fast Power Switch (SFPS)

3.1. Switching behavior

In the present paper, we are focused at the next step of this development introducing two new features to the inductive design: (i) a shuntless rings and (ii) non-coaxial arrangement of the rings (see Fig. 2). We have shown that the shuntless rings withstand powerful and durable quench without damage if the rings are made from wide tape (width > 0.2πR) [11]. This follows from the mechanism of development of the normal zone that is larger in wider tapes. In homogenous rings, the width and length of the nucleation zone are of the same order of magnitude. This means that a set of narrow tapes connected in parallel cannot replace wide tape because of smaller size of initial normal zone and therefore proportionally higher concentration of “hot spot” energy. This should cause a damage of the weakest tape with “cascading” of this damage over all narrow tapes switched in parallel.

According to previous investigations [11] tubular rings made of HTS coated tape with drastically reduced shunt (consisting of only 100 nm thick layer of Ag-Au alloy), i.e. practically shuntless tapes, exhibit extremely small, typically 50 µs duration of transition from the superconducting to the normal state. This is typically 50-100 times faster than the transition time of tape with a standard shunt. As a result a 50-100 times smaller Joule’s heat dissipating in the course of this transition is observed because the main dissipation takes place in the external resistances. By thin shuntless tape with low heat capacity, “crossing” of maximum dissipation to external shunts is very fast. This leads to minimal absorbed heat in the cold space (typically filled with liquid nitrogen).

![Figure 2. iSFCL/SFPS with non-coaxial unshunted HTS rings.](image)

On the other hand, the shuntless tapes exhibit very moderate Joule’s dissipation in quenched modus because of very high resistance of tape. The resistance may be as high as 40 Ohms per 1 m tape of
1 cm width (measured above 90 K). A voltage drop above 2 V per cm of tape length may be applied without tape damage. Usually such high resistance allows to keep tape temperature at a level which exceeds the critical temperature by only 2-10 K. This enables savings in cryo-power and a fast (0.5-3ms) recovery time.

In view of such outstanding dynamics, current limiting devices based on superconducting elements with properties described above offer very fast switching parameters. This explains also the reason why we call it Superconducting Fast Power Switch (SFPS).

3.2. Interaction between rings
We consider an ironless arrangement where the secondary HTS cylindrical rings are positioned non-coaxially, in one layer within the primary coil made out of copper (see Fig. 2). If the rings are in superconducting state, current induced in each ring should compensate the external (against this particular ring) field in a way that the magnetic flux crossing the ring equals to zero.

Since the “external” field is formed from the field of the primary coil and particular fields of other secondary rings wherein the fields are acting substantially in the same direction the rings stay “in competition” one to other: one of the rings cannot transport the screening current required to compensate external flux and quenches, thereby allowing the external flux through it, the adjacent rings have to transport less current and are with reduced current load that reduces by one step down regarding quench threshold.

Energy of magnetic field grows and, as a result, the entire inductance seen in primary circuit (connected to a power line) will also grow by a series of steps during fault.

Such behaviour is similar to “sequential” quench that may be observed in chain of superconductors with different critical currents (see Fig. 3). This process results in a controlled limitation of faults with minimum dissipation in secondary circuit, thereby reducing the LN₂ boil off rate. Now, if the fault current in the primary continues to raise, the remaining HTS rings also quench one by one.

![Figure 3](image-url). Equivalent electric schema (a) of iSFCL/SFPS based on HTS cylindrical rings positioned non-coaxially and corresponding V(I) curve (b) typical for “sequential” quench.

Equivalent electromagnetic schema of SFPS with non-coaxial unshunted HTS rings is shown in Fig. 4.

![Figure 4](image-url). Equivalent electromagnetic schema of SFPS with non-coaxial unshunted HTS rings.
3.3. Effective smoothening of fast limiting effect

The integrated impedance vs. current dependence is “smoothed” by fast reversibility (quench/recovery) of the new quench (see Fig. 5). The time evolution of averaged inductance as seen by the faulted power line is given by

\[ L_{av} = T^{-1} \int_{0}^{T} L(\tau) \, d\tau \]  

(1)

Fig 6 gives oscillographic display of time dependence of voltage and current of SFPS with 2 secondary HTS rings. A current limitation of 35% during fault is obtained with reduced heat dissipation and thereby reduced cryo-consumption power.

Figure 5. Effective smoothening of fast limiting effect. a- general behaviour of sinusoidal current by crossing quench threshold, solid curves correspond limited current; dashed curve – non-limited current; b, c – average inductance vs. current in SFPS with single ring and 3 rings respectively. \( L_{av} \) is defined in equation (1).

Figure 6. SFPS with 2 rings: time dependence of voltage and current. White curve indicates current without rings. 2 steps of quench (in different rings) is visible in blue curve. Limitation of current amplitude corresponds to about 35%. Separate quenches of different rings are visible in i-curve, better during the 2\textsuperscript{nd} and 3\textsuperscript{rd} half cycles (in the 3\textsuperscript{rd} half-cycle they are indicated as 1 and 2).
3.4. Electrical and cryogenic performance of SFPS

Electrical performance of a demonstrator SFPT based on 5 HTS rings made of YBCO coated tape is shown in Fig. 7 a. The primary coil of 0.37 m diameter and 0.07 m height included 50 copper windings. HTS rings were manufactured by Bruker HTS tape of 40 mm wide, developed for operation at fast-quench conditions [11]. A high-ohmic protection layer deposited on the top of YBCO layer together with means for insulation of the HTS layer against the substrate enabled a high resistance of the conductor after quench. This allows to reduce substantially level of cryo-losses (i) during transition to the quenched state and (ii) during long term quench. Duration of quench may exceed 10 s without tape damage.

Dependence of the inductance \( L \) vs amper-turns (Fig. 7 a) reveals a “smoothed” transition between low and high levels of the inductance corresponding to 0.9 and 1.56 mH, respectively. A sequence of 5 quenches in different rings by current ramp results in almost “smoothed” transition between \( L_{\text{low}}=0.95 \text{ mH} \) and \( L_{\text{high}}=1.56 \text{ mH} \). Low level inductance is determined by efficiency of shielding of primary flux by HTS rings, the efficiency that may always be tuned by SFPS design. Such demonstration represents a “slice” of the larger SFPS based on a number of such “slices” interconnected in a co-axial way with respect to primary coils. Fig. 7 b demonstrates current dependence of the inductive impedance in up-scaled SFPS with parameters extrapolated to 40 MVA with 2 kA nominal current. Expanded model contains 10 layers of rings, 5 ring-like assemblies in each layer (similar to Fig. 2) where each assembly is designed for a quench current 15 kA_{rms}. Primary coil consists of 77 windings with average diameter of 0.525 m and height of 0.5 m. The coil surrounds a cryo-vehicle with HTS assemblies arranged in layers mentioned above. This system exhibits a transition from 0.27 to 0.7 Ohms of the inductive impedance with “smoothed“ transition that occurs in adjustable the range, in given case between 2 and 3 kA_{rms}.

![Figure 7. a – inductance vs. primary amper-turns measured for 5-ring SFPS. “Smoothed” sequence of 5 particular quenches result in almost “smoothed” transition from \( L_{\text{low}}=0.95 \text{ mH} \) to \( L_{\text{high}}=1.56 \text{ mH} \); b – \( L(i) \) dependence extrapolated to 40 MVA with 2 kA nominal current.](image-url)

Cryo-losses of 40 MVA SFPS in comparison with standard resistive fault current limiter (SFCL) are shown in Table 1. Splicing/interconnection losses are taken into account. In resistive SFCL case [12], in accordance with employed design 45 double coils (with 4 ends) would be needed at nominal voltage of 20 kA_{rms}. Accordingly, about 200 splices or joints would be needed to provide interconnections within the SFCL. With typical resistance of 50 n\( \Omega \) of single splice the total splice resistance is estimated to \( \sim 10 \mu \Omega \) which should cause by transport of nominal current power losses of about 40 W.
At normal pressure this power corresponds to ~1 L/h loss of LN$_2$. Because of wider tapes, in SFPS these values correspond to ~20 W or ~0.5 L/h LN$_2$ loss, respectively, i.e. they are practically twice lower.

Further parameters of resistive SFCL originate from the conventional need of ~300 W cooling power (or 7 L/hour of LN$_2$) for compensation of cryo-losses in copper current feedthroughs loaded with 2000 A$_{rms}$ [13]. By resistive SFCL cooling losses in cryostat are 5 times higher because of 5 times thicker than in SFPS metallic walls needed to provide operation pressure of 5 bar [12]. Thus total LN$_2$ losses during nominal operation are 9 and 0.7 L/hour for SFCL and SFPS, respectively.

In quench modus, resistive SFCL yields high cryo loss because at least half of the nominal electrical power [12] starts to dissipate within the cryo vehicle. This corresponds to about 120 L/s or 10 L per 0.08 s-quench. In SFPS case, main power dissipation occurs during ~0.1 ms (quench transition) what results in only 2 L loss of LN$_2$ and further loss of ~2 L/sec due to rest heating power dissipating in ring assemblies being in high Ohmic state.

It is clear from Table 1 that the cryo consumption of SFPS may be so small that it enables a “stay-alone” function without cryo-cooler, only with a cryo-tank. With a 1.4 L/h loss the volume of LN$_2$ needed within half a year corresponds to 6 m$^3$. Storage and automatic filling with such or even double amount of liquid nitrogen (i.e. sufficient for 1 year operation at nominal current) seems to be realistic. This is especially attractive for high-voltage (e.g. above 250 kV) grid applications of SFPS because the short-circuited secondary rings see a maximum voltage below 200 V only. Thus no sparks and arcs are expected in the final switch.

**Table 1.** Consolidated cryo-losses (LN$_2$ evaporation) from various components: example of SFPS with performance extrapolated to 40 MVA, 2 kA, 20 kV, in comparison to equivalent conventional resistive SFCL with the same power. *)

| Design:                      | conventional resistive SFCL | 40 MVA SFPS |
|------------------------------|-------------------------------|-------------|
| HTS splices (by Rs=10$^{-8}$ Ohms$\cdot$cm$^2$) | 1 L/hour                     | 0.5 L/hour  |
| Current feedthroughs:        | 7 L/hour                      | 0 L/h       |
| Cryostat:                    | 1 L/hour                      | 0.2 L/hour  |
| Total (without ac losses)    | 9 L/hour                      | 0.7 L/hour  |

**Quench modus:**
- Losses by quench: 120 L/s vs 2 L/s
- Maximal quench duration: 0.08 s vs unlimited$^*$

*) quench durations from 2 to 300 s were tested without HTS tape damage; in general, duration is limited only by amount of available LN$_2$ (1s corresponds to about 1 L in low loss case)

**4. Summary**
- First steps in development of Superconducting Fast Power Switch (SFPS) and study of a demonstration with low cryo-consumption are successful.
- Cryo-consumption that represents the most crucial feature of HTS based electrical device is improved by a factor of >10. The cryo-consumption below 1 L/hour was estimated for 40 MW SFPS device on basis of current demonstration tests.
- SFPS based on wide HTS coated tapes shows substantially inductive impedance during current limitation and exhibits a low Joule loss.
- Impedance vs. current dependence is possible to design units for different distributions of critical current in different rings.
• SFPS is especially attractive for high-voltage (e.g. above 250 kV) grid applications because the short-circuited secondary rings see a maximum voltage below 200 V only.

Acknowledgments
Authors acknowledge assistance of Frank Mumford (ALSTOM Grid – UK) in development of principles that triggered the current study.

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