SUPERCONDUCTING FAULT CURRENT LIMITERS

The control of fault currents in electrical transmission and distribution networks is a major challenge. Short-circuit current levels are considerably larger than the rated current. All electrical equipment exposed to the short-circuit current must be designed to withstand in particular the mechanical forces under fault conditions, which are generally proportional to the square of the current. Circuit breakers that isolate the fault must be capable of absorbing the fault energy, as well as be proportional to the square of the fault current at the instant of breaker operation. Consider an infinite bus feeding a load through a transmission line and transformer with 8% combined impedance. In the event of a short circuit across the load, the short-circuit current is limited only by the line and transformer impedance. The steady-state short-circuit current will be 12.5 times larger than the rated current, and the initial transient current can reach a value about twice the peak steady-state fault current, resulting in short-circuit electromagnetic forces that are 625 times higher than the peak forces under rated conditions. To survive such a fault, all circuit components must be designed to withstand the peak forces.

A fault current limiter restricts the current fed to the fault to a lower value than with the limiter absent. Unlike mechanical breakers, where the mechanical inertia in the mechanism delays any effect on the fault current during the first few cycles, fault current limiters insert an impedance already in the first half cycle, thus limiting the peak current transient of the short-circuit event. Then all the network electrical equipment, such as lines, transformers, and circuit breakers, could be designed for smaller fault current amplitudes, which would result in a reduction of material and cost. In many transmission and distribution networks, load growth, distributed generation, and interconnections have produced increased fault levels that exceed the capability of the installed circuit breaker base to interrupt prospective fault currents. In some situations, the fault levels exceed the available ratings for circuit breaker replacement or upgrading, and economically or operationally attractive interconnections cannot be made. With the introduction of a fault current limiter, a system could use breakers with a smaller interrupting rating than the system fault level. Thus electrical grids can be interconnected to produce stiffer, more reliable systems without upgrading existing breakers to higher interruption ratings.

No fault current limiter technology is widely accepted or used today. Superconducting fault current limiters (SFCL) form one class of fault limiting technology under active development. After several technical generations of development, niobium-based low temperature superconductor (LTS) technology is mature enough for consideration by the electric utility industry. However, market penetration of LTS devices has been impeded by high cost and the use of liquid helium (LHe) cooling. The 1986 discovery of a new class of ceramic high temperature superconductors (HTS) (1) and the subsequent active development of HTS raised hopes for inexpensive superconductor (SC) applications due to cheaper HTS conductor and significantly reduced refrigeration requirements. The discovery stimulated reevaluation of all previously proposed SC applications, including several SFCL embodiments, and prompted many innovative SFCL concepts and designs.

Many SFCL programs are active, ranging from the proof-of-concept stage all the way to precommercial prototype development. These programs are pursuing several distinct types of SFCLs, and it is not yet clear which approaches will ultimately be both technically and economically viable (2). At present there is no off-the-shelf SFCL product available in the marketplace, and even the most advanced of the several SFCL commercialization programs are not expected to be ready to offer utility-qualified products for some years to come. Here we outline the key issues of SFCL technology and application to give a basis for evaluating present and future developments.

Almost all SFCL development is targeted to power frequency grid applications. Conceptual studies of utility generation and transmission systems with a large proportion of SC generators, transformers, and transmission cable have looked to SFCLs to limit the higher fault levels inherent in the lower fault impedances of the SC system components. SFCLs would also be useful in high voltage direct current (HVDC) transmission, where currently the challenges of dc fault current interruption have not been solved. More specialized applications can be considered in high-power radio-frequency systems, magnet energization circuits associated with high-energy physics, and aerospace and shipboard systems. This article will focus on the electric utility, power-frequency type of application. Several surveys have been carried out of the applicability of SFCL technology for electric utility needs (3,4), and some studies have projected SFCL costs (5).

The most important characteristics for the user is the limiting current level. As discussed later, for most utility grid applications, a fault level reduction of 10% to 50% is needed to coordinate with existing protection, whereas for industrial end users more aggressive reduction may be appropriate. Other parameters are the trigger level for the initiation of limiting and the reset time for the limiter to re-arm after limiting operation.

Most SFCLs may be classified into (1) quenching SFCLs, which rely on the superconducting-normal phase transition to switch from a low to a high impedance; (2) desaturating SFCLs where ferromagnetic material switches between saturated and unsaturated states and the SC biases the quiescent operating point to the low-impedance unsaturated state; and (3) semiconductor SFCLs where the semiconducting elements switch to a high-impedance operating point from a low-impedance point defined by bias applied from the SC. Superconductivity is essential only to the quenching SFCL, but it is useful in desaturating and semiconductor fault limiters to reduce the bias system losses and improve system compactness.

ELECTRIC UTILITY GRID APPLICATION

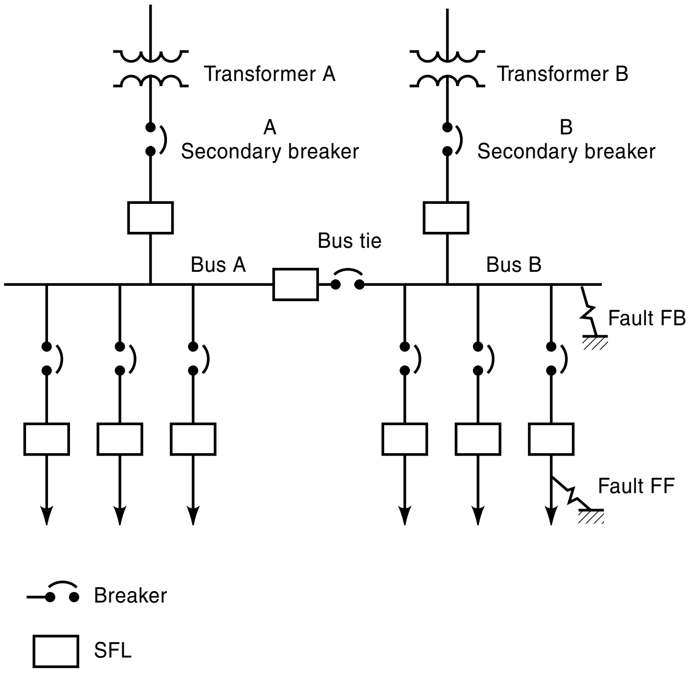

Figure 1. Superconducting fault limiter application in a substation.

To be useful, the SFCL must operate quickly enough to limit the first half-cycle of the fault so that the interrupter peak current duty is reduced. This imposes a fast SFCL triggering requirement. Most concepts are self-triggering, with the instantaneous fault current driving the SFCL transition to high impedance. Otherwise, external triggering driven by state-of-the-art relaying (detection time $\ll\frac{1}{2}$ cycle) is used. A tunable self-triggering level is a very attractive SFCL feature. After SFCL triggering, a series power circuit breaker interrupts the fault at one of the line current zeros, with an operating delay from $1\frac{1}{2}$ to 5 cycles. The SFCL must endure the limited fault current until the maximum backup breaker opening time, as determined by the utility's protection coordination. Triggering selectivity should also be considered to ensure that the SFCL does not trigger on transformer inrush and motor-starting transients.

We can distinguish between a *trimming* SFCL (where the effective SFCL impedance $Z_L < Z_s$, the system source impedance), which reduces the prospective fault current by 0–50%, and a *dominant* SFCL ($Z_L > Z_s$), which achieves reductions significantly over 50%. In existing networks that have incrementally grown to high fault levels, utilities require only trimming limiters so that the existing selective relay equipment can be retained. In fact, dominant limiters would require major reconfiguration of system protection coordination, which is always unattractive. Limiting the short-circuit current to values three to five times the rated current is a typical requirement in many cases. In some specific applications, a dominant SFCL, such as to protect a complete new installation for an industrial customer, may be used.

The possible locations for a fault current limiter in a substation are shown in Fig. 1. Two transformers feed two separate buses, providing power to several feeders. Interconnecting the two buses by closing the bus tie breaker will improve load voltage regulation and overall system reliability, at the cost of increased fault levels, because both transformers can now feed into a fault. Fault current limiters are installed in series with all breakers. In the case of a bus fault (shown as FB), the fault current limiter in series with the B transformer secondary side breaker limits the short-circuit current. In the case where the bus tie breaker is closed, the fault current limiter in the bus tie reduces the short-circuit current contribution from the A transformer. Should a feeder experience a fault (shown as FF), the limiter in the feeder circuit reduces the short-circuit current. If the A transformer was a later installation and the parallel connection of both buses is desirable, the installation of the fault current limiter in the bus tie connection could enable continued safe operation of the system with the original breakers.

For an SFCL device to be accepted in an electric utility system, it must meet general safety, reliability, availability, basic insulation impulse level (BIL), and overload requirements and ratings comparable to other utility components like transformers or circuit breakers. Currently there are no standards for SFCL application to utility systems. Pertinent sections of standards for other system components can be adapted to meet the fault current limiter design requirements. The efficiency should be above 99%. The SFCL must operate for reclosure duty and must be fail safe. Under all operating conditions, stray field levels accessible to personnel should be no higher than levels generated by other equipment. The exposed field levels must be limited to avoid personnel harm and projectile effects on ferromagnetic tools (and also typical debris such as discarded nuts and bolts).

In addition, the utility user must be reassured about new issues raised by the introduction of SC technology. Operational experience with utility system integration of SC is very limited. A 30 MJ/10 MW superconducting magnetic energy storage (SMES) system was installed in 1983–1984: Failures in the LHe refrigeration took the system down, but the SC coil did not fail. The operation of a small number of commercial LTS–LHe 1–3 MJ "micro-SMES" units in 480 V uninterruptable power supply systems in industrial power system environments since 1993 has demonstrated reliability matching battery systems. In addition, reliable cryogenic referigerators have been developed for commercial application in medical magnetic resonance imaging (MRI). All of the above experience points to the *technical feasibility* for an LTS–LHe SC system to achieve the same reliability as a conventional system in an electric utility environment, but such reliability has not yet been demonstrated. The ongoing testing of a 1.2 MVA HTS–liquid nitrogen (LN_2) SFL system at a Swiss hydro–electric power station (6), followed by the planned 1998 demonstration of a 21 MVA HTS SFCL system at a distribution substation (2), will provide much-needed utility environment operational experience and reliability data, particularly for HTS–LN_2 systems.

The cryogenic system of the SFCL may present the utility with a new unfamiliar consumable, the liquid cryogen. It is very unlikely that LHe will be acceptable, because of its cost and specialized handling procedures. Liquid nitrogen (LN_2) might be accepted because it is much cheaper, widely available, and already in utility use in some transmission cable applications, where it is used to freeze the oil dielectric in the course of maintenance procedures. Closed cryogenic systems are the most attractive, where limited amounts of cryogen boiloff are reliquefied, or where no liquid cryogen is used at all.

QUENCHING TYPES

The size of the SC element, which changes from a very low impedance state to a finite resistance (a quench), is based on the material properties of critical current J_c and normal resistivity ρ_n, and the system requirements of crest trigger current I_{c0} and normal state SFCL resistance R, to give a conductor cross-sectional area of I_{c0}/J_c, length $RI_{c0}/J_c\rho_n$, and volume $RI_{c0}^2/J_c^2\rho_n$. In general, high $J_c^2\rho_n$ is desirable to minimize superconductor requirement.

The fault transient is divided into three time regimes: a prelimit regime (period I) where $I < I_{c0}$ and the limiter is not yet active, a resistance growth regime (period II) where the SFCL is in a partially resistive state below the critical temperature T_c and the limiter effective resistance $R_e = V_L/I$ (V_L is limiter voltage) is rising from 0 to R, and a full-resistance regime (period III) where the SFCL temperature is above T_c and all superconductivity has quenched. Period I behavior depends on V_s, L, and I_{c0} alone.

The electrical performance in period III is analyzed in terms of an *RL* circuit transient, and the average temperature transient follows from the resulting energy absorption $R\int I^2\,dt$ divided by the SFCL mean heat capacity C (including all material coupled by thermal diffusion to the SC element over the limiting time). The behavior in period II is more complex and is best solved numerically (7). It is useful to describe the SFCL as weak or strong, based on whether R is less or more than V_s/I_{c0}. With a strong limiter, the limiter voltage will overcome the source voltage during period II at which time the fault current will peak. It is still possible that there will be a subsequent higher current peak due to the power-frequency variation of V_s. It is also useful to describe the SFCL resistance growth as fast or slow, depending on whether the limiting current at the end of period II is more or less than the quasiequilibrium fault current $I_c = V_s/\mathrm{R}$. The fast weak SFCL will not force a current peak in period II, because always $V_L < V_s$. The slow weak SFCL will force a current peak in period II because period II extends so long that the limiter current grows until the voltage across L reverses and limiter dI/dt changes sign. It should be noted that the relative strength and speed of the SFCL depend on the power system parameters as well as the SFCL parameters R, C, I_{c0} and the difference between critical and quiescent temperatures.

Four simplified cases are considered in Fig. 2 with low (weak) and high (strong) R and slow and fast dR/dt. The fast strong limiter gives the lowest peak let-through current and I^2dt to interruption, but it also will produce SFCL terminal overvoltage. Weakening a fast limiter will reduce the overvoltage at the cost of higher let-through current and I^2dt. Slowing down a fast strong limiter will increase the let-through current and I^2dt and may increase the overvoltage. Clearly SFCL strength and speed are both desirable for the primary function of current limiting, but they will produce overvoltage. If only weak limiting is desired, the limiter overvoltage can be controlled by speed adjustment, and in fact all overvoltages can be suppressed by keeping speed below a particular threshold.

Period III continues until either the primary or backup circuit breaker interrupts the fault. Here the normal state SC element carries a large current and dissipates high power, which dominates total SFCL heating. For example, a resistive quenching SFCL that trims the fault level of a 345 kV transmission system (with X/R ratio 15) by 10% from 70 kA to 63

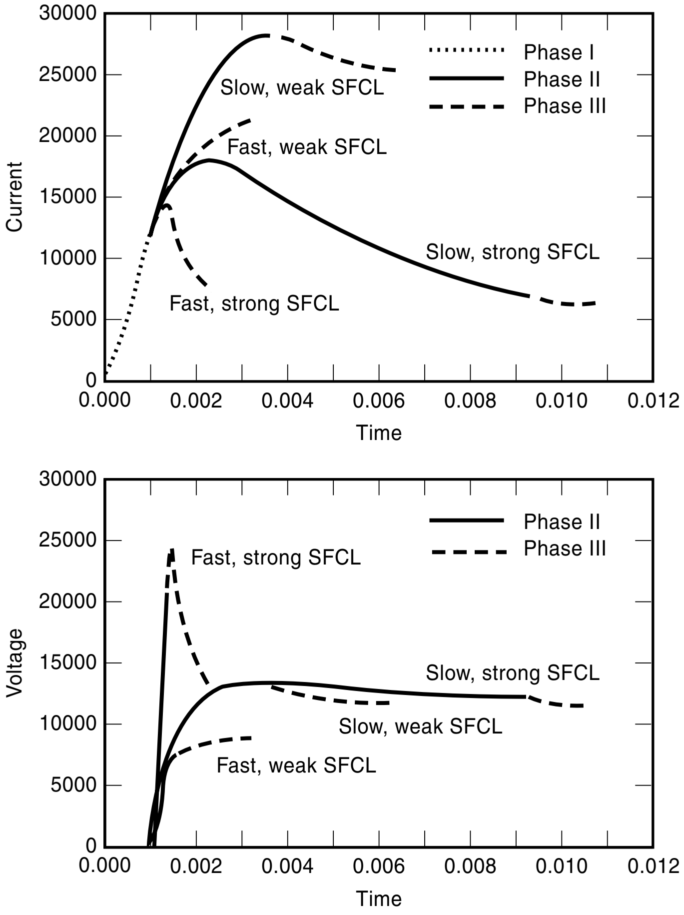

Figure 2. Four types of quenching SFCL performance depending on limiter strength and speed. Direct source voltage is applied; hence, power frequency effects are absent.

kA will dissipate 4.8 GW per quenching SFCL phase during period III. The main challenge in quenching SFCLs is SC energy management under fault conditions.

Quenching SFCLs are *in-line* (line current flows in the SC element) or transformer-coupled. In all in-line quenching SFCLs, SC heating (and thus the amount of SC and cryogenic system size and capacity) is reduced by a parallel fault current bypass resistor (8), inductor (9), or varistor (10) with lower effective impedance than R. The SFCL-limiting impedance is of course reduced, but the symmetrical SC current is also reduced. The bypass element is large with significant (but not prohibitive) cost. Both SC and conventional (copper conductor) bypass inductors have been proposed. There is little to recommend the SC variant because it would need to be rated to the fault current level for both currents and forces. A conventional reactor could be quite modestly sized to achieve the necessary transient duty, and a bypass resistor would also be reasonably sized. In weak current limiting applications, when designing for the same peak SC element temperature limit, significantly more SC material will be required for the resistive bypass design. A bypass varistor would have the additional benefit of limiting the SFCL transient overvoltage, but it has a high-energy capability requirement.

All in-line SFCLs require cryogenic current leads to connect the line current to the cryogenic system. These leads must be thermally rated for the SC element fault transient current and will become the dominant heat leak into the cryogenic system. Respectably rated distribution-level in-line SFCLs have been built with both inductive (9) (6.6 kV/1.5 kA) and resistive (8) bypass (7.2 kV/1 kA). Both used relatively short lengths (on the order of 100 m) of expensive power-frequency capable ultrafine filament NbTi superconductor with high-resistivity cupro-nickel stabilizer matrix, operating with LHe cryogen at 4 K. Important design issues include ac derating of multistranded conductor from single-strand dc values of I_c, immobilization of the conductors to avoid spontaneous quench due to conductor movement, and use of cryocoolers to produce zero-helium-boiloff systems. Heat losses from induced currents in the metallic cryostat and ac losses in nonstranded current leads and lead-to-SC wire joints were a problem. It is expected that limiting will deposit several megajoules in the cryostat, leading to significant LHe vaporization, which must be vented or captured and reliquefied. Open-cycle operation (venting the boiloff) will drive the LHe replenishment requirement, whereas the reliable reliquefaction required for a closed system is technically challenging.

HTS materials have been applied to in-line SFCLs, but at a more modest scale than the NbTi devices because of the difficulty in producing transposed multifilamentary conductors for low ac loss. An advantage of HTS materials is the relatively high ρ_n, which can exceed 10 $\mu\Omega$m. Modeling studies (10) suggest that J_c of at least 10–100 MA/m^2 (1–10 kA/cm^2) is required. The high ρ_n drives designs to relatively low SC volumes and high peak temperatures. Extra heat capacity may be added (11) by using thin (0.2–2 μm) HTS films deposited onto sapphire or YSZ (yttria-stabilized zirconia) substrates, which provide much-needed heat capacity. It remains to be seen whether the preferred in-line HTS element geometry will be wound multifilament or thin film.

In the *shielding* SFCL, the SC is coupled to the line current by transformer action [Fig. 3(a)] and forms a shorted winding. A preferred geometry is a single turn of HTS material: Bi-2212 material is commercially available in tubular sizes up to 40 cm diameter (12). The thermal transient can be analyzed by the previously derived equations after the device circuit is transformed by the turns ratio to a T-equivalent circuit. The insertion impedance will be the leakage inductance between the line and SC windings (13), and the limiting impedance will be the magnetizing inductance in parallel with the SC winding normal R. Desirable features of the shielding SFCL include the isolation of line current and potential from the SC element and no requirement for cryostat current leads. Several groups (14–16) are actively pursuing this promising approach and 6 months of operating experience protecting a hydroelectric plant auxiliary transformer circuit has been reported for a 1.2 MVA 10.5 kV Bi-2212 LN$_2$-cooled shielding SFCL (6). Design challenges include the reduction of cryostat circulating currents by the use of nonmetallic cryostats, thus minimizing circulating currents in the metalized multilayer insulation; the mechanical support of transient bursting or compressive forces on the HTS shield; the amelioration of transient thermal inhomogeneity; and optimization of recool time. Most designs utilize nonlaminated ferromagnetic cores. Aircore devices will have larger leakage impedance. Control of shielding SFCL trigger level has been proposed by using a tertiary winding (16).

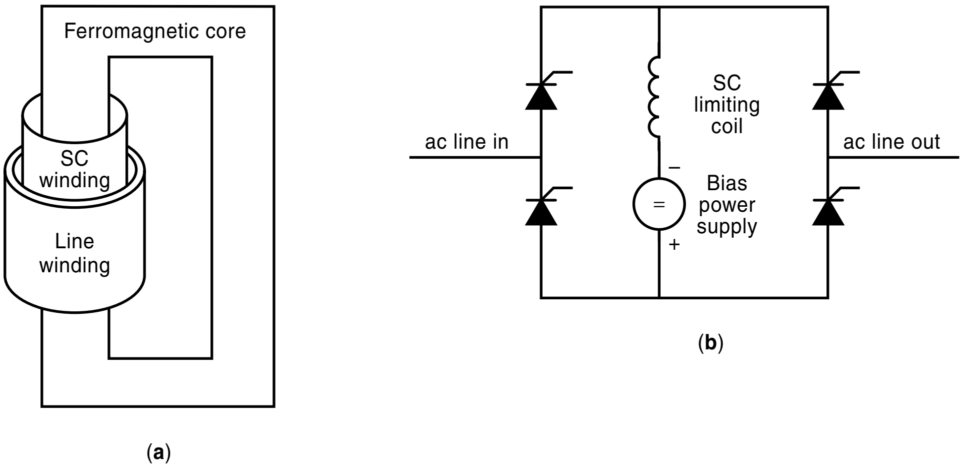

Figure 3. Principles of shielding and semiconductor SFCLs: (a) shielding SFCL, (b) semiconductor bridge SFCL.

A quenching-type SFCL operation may be self-initiated by the fault current as discussed previously, or some quenching mechanism (17) may be externally triggered by a fault detection relay. Digital microprocessor-based relaying is now capable of giving subcycle fault detection, so that detector delay is no longer a barrier. Several trigger methods have been proposed, including discharging a capacitor to give a magnetic field pulse from an auxiliary coil, discharging a capacitor to add an extra overcurrent component, triggering heaters on the SC, or sending a warm cryogen burst into the cryostat. Currently, most SFCL development is aimed at self-triggering using fault overcurrent alone. However, in later generations, commercial SFCLs will be differentiated by the triggering system to maintain trigger level control independent of SC property variations and cryogenic operating point variability and to give flexibility in setting the SFCL trigger level.

Under fault limiting, some parts of the SC element will enter the lossy period II regime before others as a result of local variations in material quality, temperature, and magnetic field. The concern is whether such locations will bear a disproportionately large part of the complete limiting burden, in terms of temperature, electric field, or mechanical stress. This has been observed in both analysis and experiment (7,18), and significant thermal damage has been reported (14). For HTS systems, quench propagation is so slow (centimeters per second) as to be ineffective during power-cycle time periods, whereas LTS systems' faster propagation (meters per second to kilometers per second) may overcome inhomogeneous initiation. This inhomogeneity is most critical when the peak fault current is close to the trigger current, leading to a prolonged period II with incomplete fault current commutation to the bypass element (if present). Thus *every* quenching SFCL will be vulnerable when the fault occurs at the system phase corresponding to the lowest prospective fault current and should be designed to be capable of withstanding inhomogeneous initiation until the interrupter opens on a current zero.

After operation, a quenching SFCL must recool to its operating temperature before becoming available again. The cryogenic system temperature profile is inverted, with a "hot" SC and "cool" thermal shield. A high heat capacity thermal ballast to level the recool system thermal load is attractive. No matter what the recool system, the SC element reset time is seconds or longer, a major shortcoming for reclose-type fault relaying systems. Multiple parallel SFCL elements are a common solution, so that a cold element is available immediately after SFCL operation; the drawback is increased system complexity and cost from duplication of the SC element, thermal decoupling between elements, and a switching subsystem.

FERROMAGNETIC TYPES

An SFCL using the principle of ferromagnetic desaturation was built in the early 1980s (19). A coil wound on a closed iron core will have a very high ac impedance when unsaturated. If, however, the iron core is saturated, the same coil will exhibit a very low impedance. Two cores are used per phase, each with an ac winding carrying the line current and also an SC dc bias winding. The dc bias windings are connected to saturate the two cores in opposite directions. The ac windings are series connected so that instantaneous line current adds to one core's bias MMF and substracts from the MMF of the other core. Under normal operation, both cores are so heavily saturated by the dc bias current that the MMF contribution of the ac does not bring either core out of saturation, and the impedance of the core is small. Under short-circuit conditions, however, each half wave of the higher ac fault current brings each core out of saturation in turn, thus inserting a high impedance into the circuit and limiting the current. At the fault current peak, the cores' resaturation (in the opposite polarity to the quiescent state) must be limited. In a three-phase system, six cores are necessary, two for each phase, but a single SC dc bias winding (and cryostat enclosure) passing through all six core windows can be used. A single phase, 3 kV, 556 A prototype using an LTS coil was built and tested with peak short-circuit currents of close to 15 kA. Although the device performed as predicted, no commercial units were ever built because of the large size of a transmission system sized unit. The total core volume required corresponds to a transformer rated at twice the fault volt-amperes. The desaturating SFCL does not necessarily quench during limiting, so that it has no reset time delay, and the limiting level can be varied by adjusting the dc bias current.

The impedance of a series line reactor can also be changed by moving armature methods that vary the effective gap of the reactor magnetic circuit. One approach under construction (20) uses a mechanically balanced disk (hypercooled to 50–70 K for enhanced magnetic and conductivity properties) to rotate magnetic and nonmagnetic sectors in and out of the gap, in times below $\frac{1}{4}$ cycle. The rotation is induced by inverter-fed HTS coils, controlled by line overcurrent relaying. Using SC in the rotation control coils significantly reduces device quiescent losses.

SEMICONDUCTOR TYPES

The nonlinear resistance of semiconductor junctions is used in the bridge-type fault current limiter, which combines power electronics and an SC coil (21). Figure 3(b) shows the circuit of a single phase. A bias power supply provides a current in all four semiconductors. As long as the load current is less than the bias current, all four semiconductors are forward biased, and the ac load current flows unimpeded by the bridge circuit, assuming negligible losses in the semiconductors. In the quiescent condition, each thyristor conducts half the bias current superimposed with half of the line current. When a short circuit occurs, one pair of semiconductors is turned on, and the other pair is turned off in each half cycle, automatically inserting the bridge inductor into the circuit. The inductor limits the fault current. Because the inductor carries a bias current under normal condition, use of an SC coil reduces the overall system losses. The bridge-type fault current limiter has several attractive features, such as automatic insertion of the current-limiting reactor, reduction of the first half-cycle short-circuit current, precise control of the amplitude of the short-circuit current, complete current interruption in less than a cycle if desired, operation with multiple fast reclosures, and high efficiency. In addition, it is conceivable to use the controlled thyristor bridge for other transmission or distribution network functions such as var control. For distribution and transmission system semiconductor SFCLs, the equivalent thyristors indicated in Fig. 3(b) are series strings of thyristors, similar to those used in static var compensators or electronic transfer switches. A 2.4 kV, 2.2 kA single-phase fault current limiter was successfully tested in 1995 and a 15 kV, 800 A, three-phase unit is being designed to be tested in 1998 (2).

OTHER TYPES

SFCL designs where the limitation arises from magnetic circuit unbalance under fault conditions have been proposed—for example, with a three-phase SC winding on a common core (22). The positive and negative sequence inductances equal the device leakage inductance, whereas the zero-sequence inductance equals three times the self-inductance. Single line-to-ground faults, which are the most common, are then limited by the magnetics alone, without quench or thermal recovery delay, whereas the rarer two- and three-phase faults will be limited by in-line SC winding quench. Thus, the SC winding thermal performance must be designed as for all in-line quenching SFCLs. An HVDC transmission SFCL (23) has balanced positive and negative line currents canceling in the magnetic circuit, whereas ground faults will unbalance the SFCL. Under these conditions, the SFCL inductance limits the fault current dI/dt until the core saturates.

SUPERCONDUCTOR REQUIREMENTS

Either niobium-based LTS or ceramic HTS materials may be considered. LTS conductor technology is relatively mature, with kiloampere-rated commercial conductor optimized for either ac or dc operation available in long lengths from several vendors. Operating $J_c s$ are in the gigampere per square meter range and operating temperatures are up to 6 K (NbTi) or 14 K (Nb_3Sn). To produce the required normal-state resistance in quenching SFCLs, the LTS conductor must have high values of effective ρ_n, which is governed by the stabilizer resistivity. The highest values (in available conductors) of about 30 nΩm (300 K) are achieved with CuNi alloy. Elementary power frequency conductor strands have 10–100A I_c and pass through two levels of cabling and twisting to achieve the required kiloampere-class I_c. At each level of cabling, the strands are grouped around a copper core, which enhances quench propagation. Current sharing is a problem that is further accentuated when kiloampere-class conductors must be paralleled to operate at 10–100 kA-class transmission network-rated currents. Such an ac conductor is more expensive than a dc conductor. Desaturating and semiconductor SFCL types do not need the same high ac performance and use more economical dc LTS conductors. The major drawback of LTS conductors is the refrigeration and cooling required to maintain the required operating temperature.

Bulk, film, or wire/tape HTS conductors can be used in SFCLs. Bulk rings or tubular cylinders, particularly useful for shielding SFCLs, have been manufactured from Bi-2212 (12), Bi-2223 (24), and YBCO (9). All the materials have T_c above 85 K, effective J_c in the 0.1–0.5 GA/m^2 range at 77 K, and ρ_n around 10 μΩm. Even though bulk Bi-2212 parameters are overall no better than the competing materials, Bi-2212 has the most promise because there are practical manufacturing techniques to produce technically useful cylinders with up to 8 mm wall thickness and 40 cm diameter. Bulk forms are also used as current leads operating between T_c and T_0. HTS materials show significantly higher $J_c s$ in thin films. For example, 200 nm-thick YBCO on a CeO_2-buffered sapphire substrate exhibited $J_c = 30$ GA/m^2 and was investigated for quenching SFCL designs (11). The substrate heat capacity and heat transfer to LN_2 cryogen limits the temperature rise. Such high J_c requires using a stabilizer parallel layer to protect against catastrophic local overheating, so that the high intrinsic ρ_n is not used. YBCO thin film panels up to 20 × 20 cm have been tested, which could be used in arrays to produce quenching SFCLs. Thick Bi-2212 films are also useful: an array of MgO substrate cylinders (45 cm diameter, 12 cm long), each supporting an 0.5 mm Bi-2212 layer, has been used in a 6.6 kV, 400 A shielding SFCL (25). Thick film J_c's are similar to bulk HTS material.

The thrust of HTS wire and tape development is to develop stabilized conductor for magnet applications. Bi-2223 conductor, produced by the powder-in-tube (PIT) process, is currently closest to commercialization but limited to low operating magnetic field levels. The silver stabilizer of PIT conductor (with ρ around 4 nΩm at 100 K) bypasses the much higher intrinsic Bi-2223 ρ_n. Multifilamentary twisted conductors are under development to produce lower ac losses. The manufacture of wire from other HTS materials such as Bi-2212 and YBCO is also under active development, and it is premature to predict which material will be most applicable to SFCLs.

The main attraction of HTS materials over LTS for SFCLs is higher operating temperatures and lower refrigeration costs. Present HTS T_c's point to useful operating temperatures in the 30–60 K range. As in other HTS applications, tradeoffs must be made between the advantages of using cheap LN_2 cryogen (77 K operation), larger amounts of HTS, more exotic cryogens (e.g., liquid neon, boiling at 27 K), or none coupled with better use of the HTS (lower operating temperatures).

CRYOGENICS

Cryostat thermal design is of paramount importance because the required cooling power is an important part of the operating cost. The quiescent cryostat heat budget consists of SC ac losses, ambient-to-cryogenic current lead heat leak, dielectric losses, and other conduction and radiation to the cryostat. Even though the design and selection of superconductor for low losses have been already discussed, and cryostat and current leads design is well understood, dielectric ac losses present a less-appreciated heating mechanism. The heat dissipation for insulation deployed in high ac electric field regions should be determined from cryogenic loss tangent. Transmission and distribution-rated in-line SFCLs using HTS may have quiescent heat loads 300 W and up as a result of ac loss and current lead penetrations. In all cases, a closed system needs refrigeration capacity to extract the significant heat leak. When refrigerator power is interrupted, the cryostat temperature will rise at a rate governed by ac losses, resistive losses, heat leak, and heat capacity, and ultimately the SC system will lose superconductivity. Auxiliary power interruptions are quite likely in an electric utility setting, and an SFCL must have some thermal ride-through capability. Electric utilities will find the cooldown time to operating temperature an important parameter. Liquid cryogen-based cooldowns may take as little as a few hours, whereas refrigerator cooldown may take many hours to days.

SFCL cryostats may use liquid or gaseous cryogen for heat transfer and storage or may operate under vacuum. Cryogen consumption must be kept low to avoid replenishment servicing any more often than annually, so refrigeration must have the capacity to meet the quiescent heat leak. In the typical power and temperature range for LTS systems, two-stage Gifford-McMahon (GM) cycle cryocoolers [with possibly a Joule-Thompson (JT) valve] are typical, whereas for HTS systems, one- or two-stage GM or Stirling cycle cryocoolers are candidates. The energy efficiencies of these refrigerators are well below the Carnot cycle limit, and typically a 7 kW helium compressor will be required for 2–3 W cooling at 4 K or 100–200 W at 80 K. The maintenance interval of cryocoolers depends on internal seal wear, oil mist freeze-out, and JT valve clogging. Use of a good oil-free high-pressure ambient temperature helium compressor gives maintenance intervals longer than one year.

CONCLUSION

SFCL is an emerging technology that is being driven by the confluence of superconductor capability developments and electric utility need. Fault current limiters would enable utilities to reap the economic benefits of operating transmission lines at the highest possible power transfer levels and the operational benefits of transmission system interconnection. High-temperature superconductor developments may soon become commercially available to enable productization of some of the many SFCL approaches under development at present. The utility requirements of equipment robustness and reliability present a challenge for SFCLs which can be technically met. A number of utility demonstration projects of SFCLs are either underway or close to being underway, which will provide much-needed operational, robustness, and reliability data. A yet unresolved issue is ultimate SFCL cost resulting from the inherent costs of high-technology cryogenic and superconducting systems. There is scope for significant inventions and improvements in fundamental SFCL concepts and their implementation and integration into electric transmission and distribution systems and components.

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