



## **Superconductors As Surge Current Protectors**

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***Abstract:***

*Modern Power Systems are growing fast with more generators, transformers and large network in the systems. The installation, running and maintenance costs of the power system equipment are more. Whenever a fault occurs, there is a need for the protection of these systems. Power System Protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network. Superconductors are one of the last great frontiers of scientific discovery. Here, in this paper we discuss the use of Super Conductors as protective devices for Surge Current Protection. Superconductors conduct electricity offering zero resistance below certain temperatures. We study different types of super conductor fault current limiters and their working.*

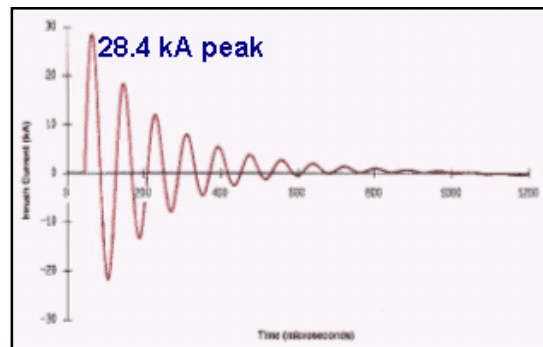
## 1.Introduction

Before knowing how the super conductors acts as surge current protectors let us concentrate on what is surge current? What it does to the power system? And what are super conductors? Meissner Effect and different types of super conductor fault current limiters.

## 2.Surge Current

The maximum instantaneous input current drawn by an electrical device when first it is turned on is defined as surge current. It is also known as Inrush current or Input Surge Current or Switch-on Surge.

Alternating current electric motors and transformers may draw several times their normal full-load current when first energized, for a few cycles of the input waveform. Power converters also often have inrush currents much higher than their steady state currents, due to the charging current of the input capacitance. The selection of overcurrent protection devices such as fuses and circuit breakers is made more complicated when high inrush currents must be tolerated. The over current protection must react quickly to overload or short circuit but must not interrupt the circuit when the (usually harmless) inrush current flows.



*Figure 1*

The only limits of the surge current are the line impedance, input rectifier drop and the capacitor equivalent series resistance.

High inrush current can affect the electrical systems by tripping fuses and circuit breakers unnecessarily. If inrush protection is not in place, relays and circuit breakers must be rated that are rated higher than any possible inrush current. Inrush Current can

also cause pitted contacts on switches and relays due to arcing of the contacts. Inrush Current can be as high as 100 times the normal steady state current and lasts for less than half a normal 60 hertz cycle.

This surge current can cause component damage and/or failure within the equipment itself, blown fuses, tripped circuit breakers and may severely limit the number of devices connected to a common power source.

### **3.Super Conductor**

An element, inter-metallic alloy or compound that will conduct electricity without resistance below a certain temperature. The Dutch Physicist Heike Kamerlingh Onnes of Leiden University was the first person to observe superconductivity in mercury.

Superconductivity is a phenomenon of exactly zero electrical resistance certain materials when cooled below a characteristic critical temperature. It is a quantum mechanical phenomenon.

Types of Superconductors:

- Low Temperature Superconductor
- High temperature Superconductors

LTS are the substances that lose all resistivity close to 4K, a temperature attainable only by liquid helium.

HTS are the substances that lose all resistance below temperature main tamable by liquid nitrogen.

Examples of LTS: Lead and Mercury – common LTS Other LTS are Ti, V, Zr, Nb etc.,

Examples of HTS: YBCO, BSCCO, LSCO, etc.,

- Meissner Effect:

The Meissner effect is the expulsion of the magnetic field from a superconductor during its transition to the superconducting state. The German physicists Walther Meissner and Robert Ochsenfeld discovered the phenomenon in 1933 by measuring the magnetic field distribution outside superconducting tin and lead samples. The magnetic flux is conserved by the superconductor, when the interior field decreased the external field is increased.

- Fault Current Limiter:

A Fault Current Limiter is a device which limits the prospective fault current when a fault occurs. Generally fault current limiters are superconductor fault current limiters.

Superconducting Fault Current Limiters are described as being in one of the two major categories:

- Resistive
- Inductive.

First applications for FCLs are likely to be used to help control medium-voltage electricity distribution systems, followed by electric-drive ships: naval vessels, submarines and cruise ships. Larger FCLs may eventually be employed in high voltage transmission systems.

Fault-current limiters using high temperature superconductors offer a solution to controlling fault-current levels on utility distribution and transmission networks. These fault-current limiters, unlike reactors or high-impedance transformers, will limit fault currents without adding impedance to the circuit during normal operation. Development of superconducting fault-current limiters is being pursued by several utilities and electrical manufacturers around the world, and commercial equipment is expected to be available by the turn of the century.

#### **4.Fault-Current Problem**

Electric power system designers often face fault-current problems when expanding existing buses. Larger transformers result in higher fault-duty levels, forcing the replacement of existing bus work and switchgear not rated for the new fault duty. Alternatively, the existing bus can be broken and served by two or more smaller transformers. Another alternative is use of a single, large, high-impedance transformer, resulting in degraded voltage regulation for all the customers on the bus. The classic tradeoff between fault control, bus capacity, and system stiffness has persisted for decades.

Other common system changes can result in a fault control problem:

- in some areas, such as the United States, additional generation from co generators and independent power producers (IPPs) raises the fault duty throughout a system

- older but still operational equipment gradually becomes underrated through system growth; some equipment, such as transformers in underground vaults or cables, can be very expensive to replace
- customers request parallel services that enhance the reliability of their supply but raise: the fault duty

### 5. Superconductive FCL:

Superconductors offer a way to break through system design constraints by presenting impedance to the electrical system that varies depending on operating conditions. Superconducting fault-current limiters normally operate with low impedance and are "invisible" components in the electrical system. In the event of a fault, the limiter inserts impedance into the circuit and limits the fault current. With current limiters, the utility can provide a low-impedance, stiff system with a low fault-current level, as Fig. 4.5 shows.

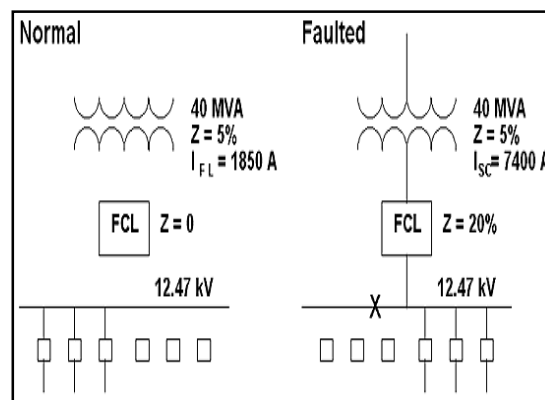


Figure 2: Fault control with a fault-current limiter

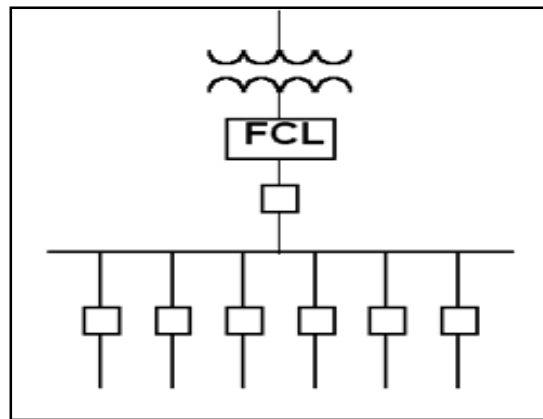
In Fig. 2, a large, low-impedance transformer is used to feed a bus. Normally, the FCL does not affect the circuit. In the event of a fault, the limiter develops an impedance of 0.2 per unit ( $Z = 20\%$ ), and the fault current  $I_{SC}$  is reduced to 7,400 A. Without the limiter, the fault current would be 37,000 A.

The development of high temperature superconductors (HTS) enables the development of economical fault-current limiters. Superconducting fault-current limiters were first studied over twenty years ago. The earliest designs used low temperature superconductors (LTS), materials that lose all resistance at temperatures a few degrees above absolute zero. LTS materials are generally cooled with liquid helium, a substance

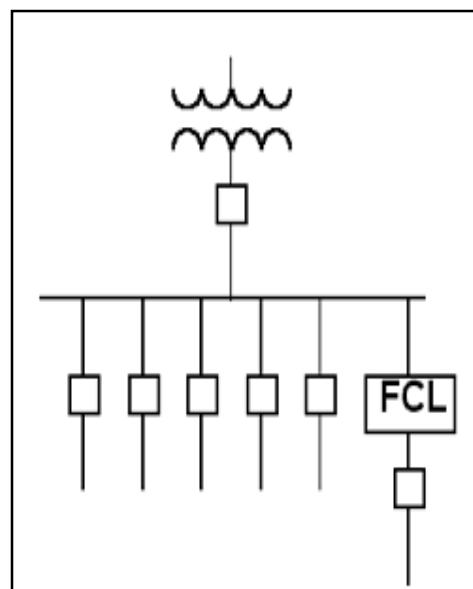
both expensive and difficult to handle. The discovery in 1986 of high temperature superconductors, which operate at higher temperatures and can be cooled by relatively inexpensive liquid nitrogen, renewed interest in superconducting fault-current limiters.

### 6. Fault-Current Limiter Applications

Fault-current limiters can be applied in a number of distribution or transmission areas. Three main applications areas are shown in Figs. 4.6, 4.7, and



*Figure 3: Fault-current limiter in the main position. The fault-current limiter FCL protects the entire bus.*



*Figure 4*

In Fig. 4 Fault-current limiter in the feeder position. The fault-current limiter FCL protects an individual circuit on the bus. Underrated equipment can be selectively protected as needed in this manner. Fig. 4.8. Fault-current limiter in the bus-tie position. The two buses are tied, yet a faulted bus receives the full fault current of only one transformer.

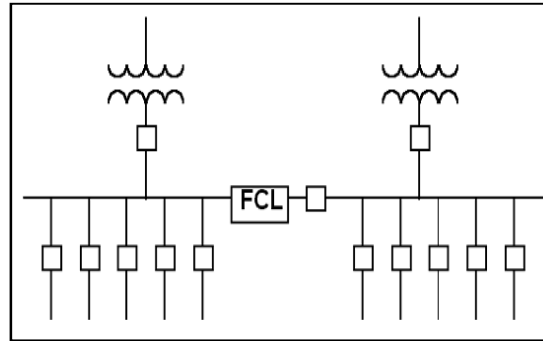


Figure 5: Fault-current limiter in the bus-tie position.

The two buses are tied, yet a faulted bus receives the full fault current of only one transformer. The most direct application of a fault-current limiter is in the main position on a bus (Fig. 5). Benefits of an FCL in this application include the following:

- a larger transformer can be used to meet increased demand on a bus without breaker upgrades
- a large, low impedance transformer can be used to maintain voltage regulation at the new power level
- $I^2t$  damage to the transformer is limited
- reduced fault-current flows in the high-voltage circuit that feeds the transformer, which minimizes the voltage dip on the upstream high-voltage bus during a fault on the medium-voltage bus

An FCL can also be used to protect individual loads on the bus (Fig. 4.7). The selective application of small and less expensive limiters can be used to protect old or overstressed equipment that is difficult to replace, such as underground cables or transformers in vaults.

An FCL can be used in the bus-tie position (Fig. 4.8). Such a limiter would require only a small load current rating but would deliver the following benefits:

- separate buses can be tied together without a large increase in the fault duty on either bus

- during a fault, a large voltage drop across the limiter maintains voltage level on the unfaulted bus
- the paralleled transformers result in low system impedance and good voltage regulation; tap-changing transformers can be avoided
- excess capacity of each bus is available to both buses, thus making better use of the transformer rating

## 7. Superconductive Fault-Current Limiter Concepts

### 7.1. The Series Resistive Limiter

The simplest superconducting limiter concept, the series resistive limiter, exploits the nonlinear resistance of superconductors in a direct way. A superconductor is inserted in the circuit. For a full-load current of  $I_{FL}$ , the superconductor would be designed to have a critical current of  $2I_{FL}$  or  $3I_{FL}$ . During a fault, the fault current pushes the superconductor into a resistive state and resistance  $R$  appears in the circuit.

The superconductor in its resistive state can also be used as a trigger coil, pushing the bulk of the fault current through a resistor or inductor. The advantage of this configuration, shown in Fig. 4.9, is that it limits the energy that must be absorbed by the superconductor. The fault-current limiter FCL normally is a short across the copper inductive or resistive element  $Z$ . During a fault, the resistance developed in the limiter shunts the current through  $Z$ , which absorbs most of the fault energy

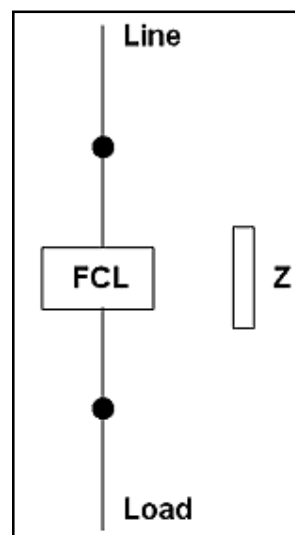


Figure 6: Fault-current limiter with HTS trigger coil



The trigger coil approach is appropriate for transmission line applications, where tens of megawatt-seconds would be absorbed in a series resistive limiter. The trigger coil configuration also allows an impedance of any phase angle, from purely resistive to almost purely inductive, to be inserted in the line.

### 8. The Inductive Limiter

Another concept uses a resistive limiter on a transformer secondary, with the primary in series in the circuit. This concept, illustrated in Fig. 4.10, yields a limiter suitable for high-current circuits ( $I_L > 1000$  A). One phase of the limiter is shown. A copper winding  $W_{Cu}$  is inserted in the circuit and is coupled to an HTS winding  $W_{HTS}$ . During normal operation, zero impedance is reflected to the primary. Resistance developed in the HTS winding during a fault is reflected to the primary and limits the fault.

The inductive limiter can be modeled as a transformer. The impedance of this limiter in the steady state is nearly zero, since the zero impedance of the secondary (HTS) winding is reflected to the primary. In the event of a fault, the large current in the circuit induces a large current in the secondary and the winding loses superconductivity. The resistance in the secondary is reflected into the circuit and limits the fault.

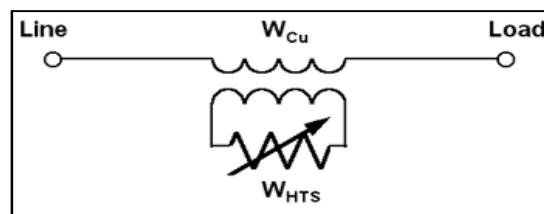


Figure 7: Inductive fault-current limiter

### 9. Japanese FCL Program

The driving factors for current limiters in Japan are somewhat different from those in the United States, given that IPPs and co generators are not as prevalent in Japan. Rather, the demand for power in Japanese metropolitan areas continues to grow because of economic growth and increased consumer use of electricity. In addition, industrial use of computers and other power-quality-sensitive equipment has forced the utilities to provide higher quality and more reliable power. The quite successful approach to improved power quality in Japan has been to increase connections between various power systems and to concentrate generation capacity in larger, more efficient units. Increasing

interconnection does, however, increase the maximum fault current available at any point in the system, and this is rapidly leading to the need for breaker upgrades and system reconfigurations. Adding to the complexity of the situation in Japan is the limited room at substation sites, which can preclude breaker upgrades. The primary need, as expressed by management of the Tokyo Electric Power Company (TEPCO), is for a limiter for the nucleus of the Japanese transmission system, the 500 kV transmission grids.

In response to this real market pull there has been a series of programs to develop fault-current limiters using a variety of methods, with recent focus on superconducting limiters (Nakade 1994). Although FCLs are not a component of the NEDO budget, TEPCO has reported that it spends about ¥100 million per year (~\$1 million) on this program, and some resistive FCL work is apparently included in the NEDO budget under the topic "Research of Superconducting Materials and Devices."

In the late 1980s, Seikei University manufactured a small-scale three-phase current-limiting reactor and demonstrated successful operation. This three-phase system introduces a large unbalanced reactance in the system to limit currents in the case of a single-phase short and quenches to introduce resistance in the circuit in the case of a three-phase fault.

Mitsubishi Electric Company (MELCO) has been participating in a MITI/NEDO FCL program since 1990. This is a resistive limiter approach using HTS films on a strontium titanate substrate that has demonstrated limiting of 400 A currents to 11.3 A. The Central Research Institute of the Electric Power Industry (CRIEPI) has developed the inductive limiter shown in Fig. 4.11 (Ichikawa and Okazaki 1995). This approach, similar to those of ABB and Siemens-Hydro Quebec, uses a cylinder of bulk BSCCO-2212 or BSCCO-2223 to separate a normal copper coil from an iron core. In normal operation, the field from the copper coil does not penetrate the superconductor; under fault conditions, however, the current induced in the superconductor is sufficient to drive it normal, and the magnetic field links the iron yoke. This greatly increases the inductance of the copper coil, thus providing current limiting. CRIEPI work has focused on ac magnetic shielding performance of bulk superconductors and their responses to fault currents. In addition, introduction of a "control ring" in the system to absorb some of the energy deposited during a fault has reduced the cooldown time of the shield following a faulted state.

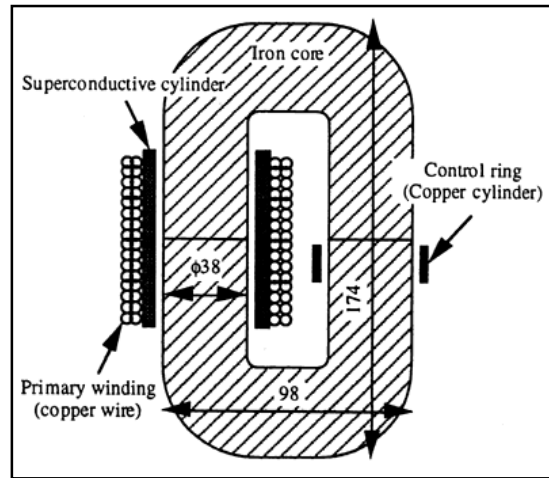


Figure 8: Schematic diagram of the CRIEPI inductive FCL (Ichikawa and Okazaki 1995).

The most extensive FCL program in Japan has been the collaboration between TEPCO and Toshiba. The long-term goal of this program is the development of a 500 kV limiter with a rated current of 8,000 A. Initial development has been focused on a distribution-level limiter designed for 6.6 kV.

As shown in Fig. 4.12, the FCL is formed by connecting four superconducting coils in a series-parallel configuration so the total inductance is minimized. One set of coils is used for each phase of the device, and limiting is accomplished by quenching the coils. The current version of the FCL shown in Fig. 4.13 uses a special low ac loss Nb-Ti conductor. Tests in a circuit with a nominal short circuit current of 25.8 kA have successfully demonstrated limiting to about 4,000 amps (Fig. 4.14).

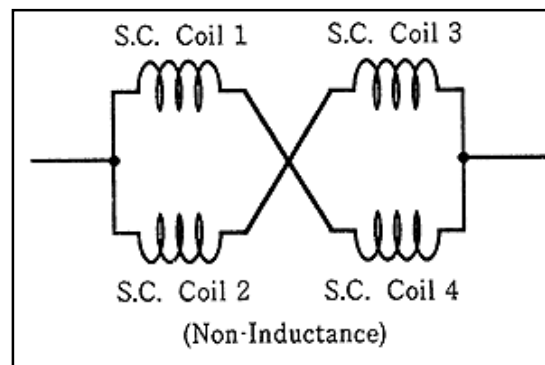


Figure 9: Configuration of coils in the TEPCO/Toshiba FCL (Nakade 1994, 34).

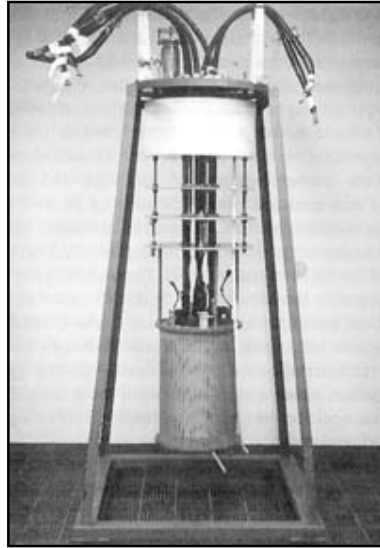


Figure 10: Exterior view of the 6.6 kV 2,000 A-class current limiter. The coil is 420 mm in diameter and 640 mm long (Nakade 1994, 35)

Recent work has included the introduction of HTS current leads to reduce the refrigeration load of the system to levels that can be handled by a 4 K Gifford McMahon refrigerator. Over three generations of the device, the heat leak has been reduced from 13.8 watts to 3.4 watts, which is nearing the required level.

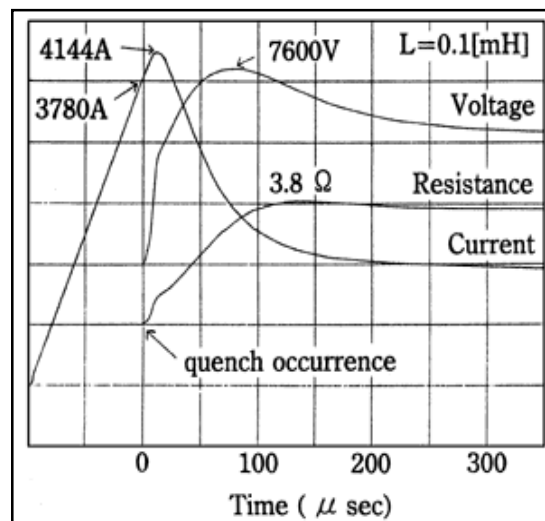


Figure 11: Current limiting characteristics of Toshiba FCL (Nakade 1994, 35).

### **10.Future Plans**

TEPCO will develop a three-phase limiter over the next three to four years and test it in the grid within this century. There are few distribution-level FCL applications seen in the TEPCO grid, however, and the current plan is to introduce solid state breakers for distribution before installing superconductive FCL. The true application for the superconducting FCL is at transmission voltages of 500 kV. The view of TEPCO researchers is that this voltage range will require the introduction of HTS coils (rather than LTS) to eliminate the helium gas from the system. Introduction of a transmission-level FCL on the grid is anticipated about 2010.

### **11.Fault-Current Limiters In Europe**

By far the most comprehensive FCL program in Europe is that being conducted by collaboration between Electricité de France, GEC Alsthom, and Alcatel Alsthom Recherché. The program's main goal is to provide FCLs for the 225 kV grid in France. The group has chosen a resistive limiter based on LTS material and has demonstrated effective operation at 40 kV (rms), with an industrial demonstration on the French 63 kV grid expected in 1998. Evaluation of the French program is beyond the scope of this WTEC study, so no visit was made to this project. Verhaege et al. (1996) provide an overview of the technology and project status.

### **12.Swiss And German FCL Programs**

Two sites the WTEC panel visited in Europe addressed FCL: ABB in Baden-Daetwil, Switzerland, and Siemens in Erlangen, Germany. ABB is pursuing a fault-current limiter concept very similar to that described above for the CRIEPI program. It is referred to as the "shielded iron core concept." It uses a warm iron core enclosed by a superconducting shield in a fiberglass Dewar. The copper primary coil is wound external to this Dewar. ABB has constructed and tested a 100 kW prototype using a stack of four Bi-2212 rings 8 cm long, and 20 cm in diameter. Operation was at 480 V with fault currents of 8 kA. A new ABB three-phase 1.2 MW FCL is now in operation in a power station in Löntsch, Switzerland.

Siemens is following two routes for FCL in a collaborative program with Hydro-Quebec Canada. At the Siemens corporate labs in Erlangen, the focus has been on resistive limiters using YBCO thin film meander lines on YSZ or on YSZ and sapphire (Gromoll et al. 1996). The advantage of this approach is that the YBCO film has a high normal

state resistance and is not shunted by normal metal, as would be the case in a composite powder-in-tube conductor. The film also has very low heat capacity, which leads to rapid switching to the normal state ( $< 1$  ms) and the possibility of rapid cool down. Analysis as of 1996 has determined that both peak let-through current and steady state limiting current decrease as  $J_c$  is raised. In addition, the design of a limiter of usable size depends strongly on  $J_c$  -- higher  $J_c$  enables a more compact design. The major focus of the program has, therefore, been the fabrication of uniform high- $J_c$  films of YBCO. Techniques investigated have included pulsed laser deposition (PLD), thermal co evaporation, and magnetron sputtering on buffered p-YSZ, unbuffered p-YSZ, and sapphire. Bi axially textured YSZ buffer layers have been fabricated on part of the p-YSZ substrates by ion beam assisted deposition. Current densities up to  $3 \times 10^6$  A/cm<sup>2</sup> have been achieved, as have good limiting performance and recovery times on the order of 1 second. The next milestone for the project is construction of a 100 KVA limiter using a cry cooler. Further details of this program are given in the Siemens site visit report (Appendix D).

Two additional German FCL projects began in January 1997. The first is a system study that will be followed by construction of a demonstration FCL. This project is a joint effort by the German utilities RWE, VEW, and Badenwerk, and by EUS GmbH and FZK. The second project involving the development of a small inductive limiter is under the auspices of the German Israel Foundation. The German participants are FZK, Hoechst AG, and the utility Badenwerk; the Israeli participants are Tel Aviv and Ben Gurion Universities. The work at Hydro-Quebec has resulted in the construction and test of a number of devices since 1992 (Fig. 4.15). The latest system operated at 450 V and 95 amps for a nominal power of 43 KVA. Two different materials were evaluated for the superconducting shield: melt-cast Bi-2212 from Hoechst, and composite reaction textured (CRT) material from Cambridge. Although successful current limiting was demonstrated, the limiter that used the Hoechst material failed during a 480 V short-circuit test due to a fracture of the superconductor (Cave et al. 1996). Subsequent analysis by Hydro-Quebec indicated that thermal stress in the bulk superconductor gave rise to the failure. The near-term future direction of this program will be concerned with improving the homogeneity, critical current density, and resistivity of the bulk superconductor.

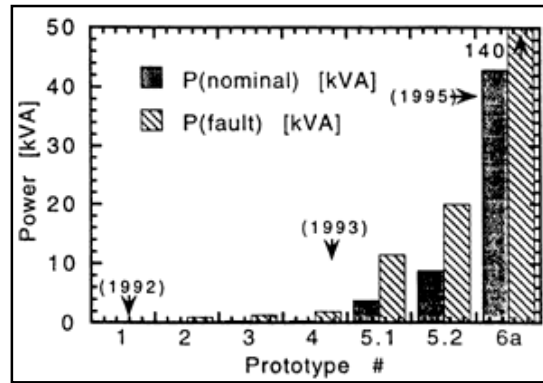


Figure 12: Power rating of the inductive limiter models built/tested at Hydro-Quebec 1992-95 (Cave et al. 1996)

### 13. Conclusion

The purpose of this paper was the study of surge current protection using superconductors. The Superconductor Fault Current Limiters offers efficient advantages to power systems and opens up a major application for superconducting materials.

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