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Surge Current Protection Using Superconductor

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Abstract

The recent growth of power circuit capacities has caused fault currents to increase. Since the protection of power systems from the fault currents is very important, it is needed to develop a fault current limiter. A fault current limiter is required to assure rapid reaction to fault currents, how impedance in normal operation, and large impedance during fault conditions. A super conducting fault current limiter (SFCL) can meet these requirements superconductors, because of their sharp transition from zero resistance at normal current to finite resistance at higher current densities, are tailor-made for use in FCLs

Keywords: *FCL-Fault Current Limiter, SFCL-Superconducting Fault Current Limiter, TVSS-Transient Voltage Surge Suppressors, SPDs-Surge Protective Devices*

INTRODUCTION

Super conductors are of two types-high temperature superconductors (HTS) and low temperature superconductor (LTS). The HTS are substances that lose all resistance below temperature main tameable by liquid nitrogen. LTS are substances that lose all receptivity close to 4k, a temperature attainable only using by using liquid helium. Cost of cooling LTS (which are mostly metals, alloys and inter mettalics) makes their use in many applications commercially impractical. HTS materials available are all made of bismuth (BSCCO) or yttrium-cup rate (YBCO). So far, various types of SCFLS have been developed (resistance, shield core type, hybrid etc.). The SCFCL offers efficient advantages to power system and opens up a major application for superconducting material.

1. Surge current

Inrush current, input surge current or switch-on surge is the maximum, instantaneous input current drawn by an electrical device when first turned on. 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 over current 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 fault but must not interrupt the circuit when the (usually harmless) inrush current flows.

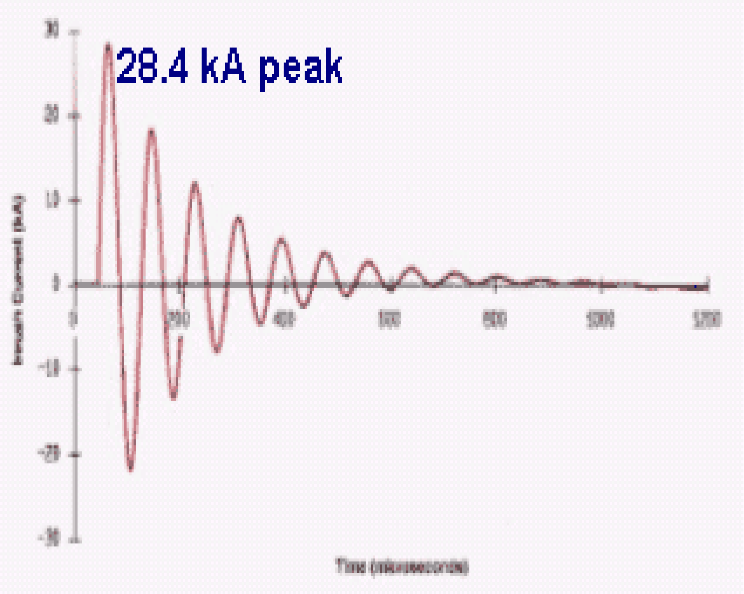


Fig. 1: Example of surge current

2. Superconductor

A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance. This means no heat sound or any other form of energy would be released from the material when it has reached "critical temperature" (Tc), or the temperature at which the material becomes superconductive.

Unfortunately, most materials must be in an extremely low energy state (very cold) in order to become superconductive. Research is underway to develop compounds that become superconductive at higher temperatures. Currently, an excessive amount of energy must be used in the cooling process making superconductors inefficient and uneconomical.

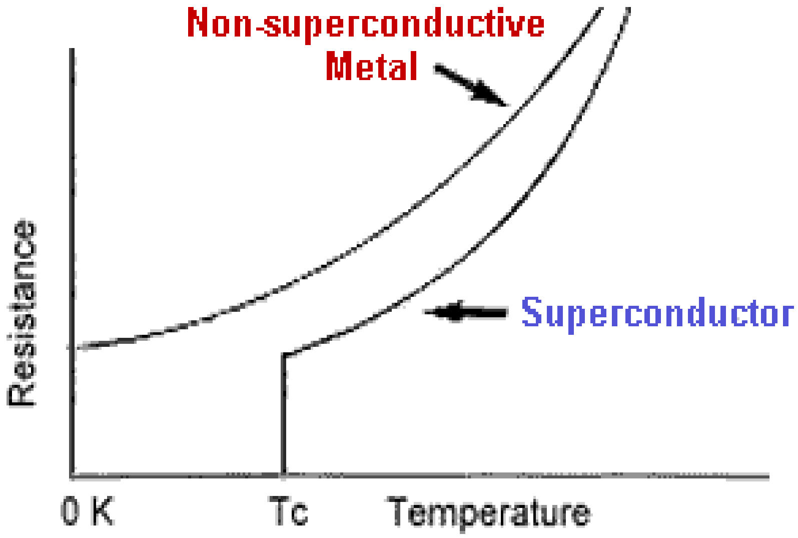
There are two types of superconductor:

a. Type 1 superconductor

The Type 1 category of superconductors is mainly comprised of metals and metalloids that show some conductivity at room temperature. They require incredible cold to slow down molecular vibrations sufficiently to facilitate unimpeded electron flow in accordance with what is known as BCS theory.

BCS theory suggests that electrons team up in "Cooper pairs" in order to help each other overcome molecular obstacles - much like race cars on a track drafting each other in order to go faster. Scientists call this process phonon-mediated coupling because of the sound packets generated by the flexing of the crystal lattice.

Type 1 superconductors - characterized as the "soft" superconductors - were discovered first and require the coldest temperatures to become superconductive. They exhibit a very sharp transition to a superconducting state (see above graph) and "perfect" diamagnetism - the ability to repel a magnetic field completely. Below is a list of known Type 1 superconductors along with the critical transition temperature (known as Tc) below which each superconducts. The 3rd column gives the lattice structure of the solid that produced the noted Tc. Surprisingly, copper, silver and gold, three of the best metallic conductors, do not rank among the superconductive elements.



b. Type 2 superconductor

Except for the elements vanadium, technetium and niobium, the Type 2 category of superconductors is comprised of metallic compounds and alloys. The recently-discovered superconducting "perovskites" (metal-oxide ceramics that normally have a ratio of 2 metal atoms to every 3 oxygen atoms) belong to this Type 2 group. They achieve higher Tc's than Type 1 superconductors by a mechanism that is still not completely understood. Conventional wisdom holds that it relates to the planar layering within the crystalline structure. Although, other recent research suggests the holes of hypocharged oxygen in the charge reservoirs are responsible. (Holes are positively-charged vacancies within the lattice.) The superconducting cuprates (copper-oxides) have achieved astonishingly high Tc's when you consider that by 1985 known Tc's had only reached 23 Kelvin. To date, the highest Tc attained at ambient pressure for a material that will form stoichiometrically (by direct mixing) has been 147 Kelvin. It is almost certain that other, more-synergistic compounds still await discovery among the high-temperature superconductors.

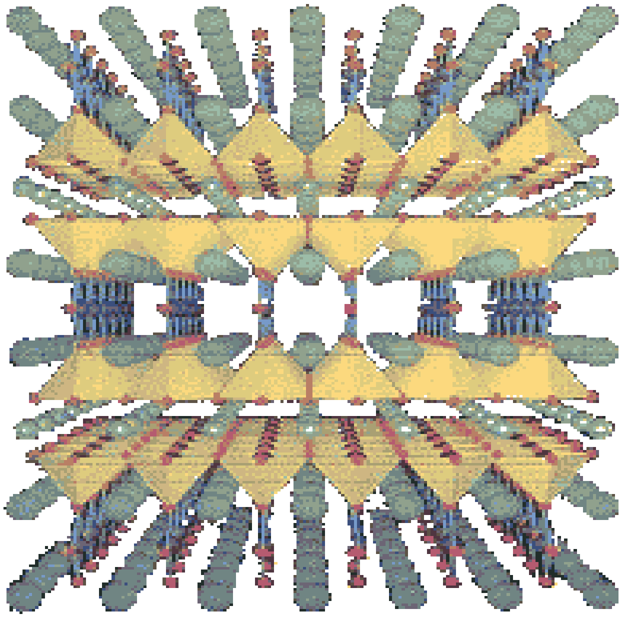


Fig.3.Type-2 Superconductors

c. Meissner Effect

Some materials tend to expel the magnetic field; these materials are said to be “diamagnetic”, but the effects are very weak. For instance, water and the human body are diamagnetic materials. However, because of the Meissner effect, the superconducting material creates currents which completely oppose the magnetic field applied by a magnet.

A superconductor in a Meissner state is hence a perfect diamagnet.

Fig.4.Meissner effect

The currents responsible for this effect do not need any energy to continue, but the system must apply the initial energy to make them accelerate until they reach the value that enables the cancellation of the external magnetic field. If the magnetic field to be expelled is too strong, the system will not be able to develop the necessary supercurrents; therefore there will be no superconductivity and the sample will simply behave as a normal metal. The critical magnetic field over which the material will not become superconducting even when cooled is called Bc. Superconductivity depends on both the temperature and the magnetic field, which can be represented on a phase diagram.

II. HISTORY

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic flux fields occurring in certain materials, called superconductors, when cooled below a characteristic critical temperature. It was discovered by Dutch physicist Heike Kamerlingh Onnes on April 8, 1911, in Leiden. Like ferromagnetism and atomic spectral lines, superconductivity is a quantum mechanical phenomenon. It is characterized by the Meissner effect, the complete ejection of magnetic field lines from the interior of the superconductor as it transitions into the superconducting state. The occurrence of the Meissner effect indicates that superconductivity cannot be understood simply as the idealization of perfect conductivity in classical physics.

The electrical resistance of a metallic conductor decreases gradually as temperature is lowered. In ordinary conductors, such as copper or silver, this decrease is limited by impurities and other defects. Even near absolute zero, a real sample of a normal conductor shows some resistance. In a superconductor, the resistance drops abruptly to zero when the material is cooled below its critical temperature. An electric current flowing through a loop of superconducting wire can persist indefinitely with no power source.

In 1986, it was discovered that some cuprate-perovskite ceramic materials have a critical temperature above 90 K (−183 °C). Such a high transition temperature is theoretically impossible for a conventional superconductor, leading the materials to be termed high-temperature superconductors. The cheaply-available coolant liquid nitrogen boils at 77 K, and thus superconduction at higher temperatures than this facilitates many experiments and applications that are less practical at lower temperatures.

Many years ago, Transient Voltage Surge Suppressors (TVSS) were ‘invented’ and implemented without a full understanding of surges or safety issues. Since those early days, TVSS have been renamed to Surge Protective Devices (SPDs). The knowledge and regulatory base has grown substantially.

As a generalization, surge protectors ‘activate’ upon sensing overvoltage. Overvoltage is different than overcurrent. For example, overcurrent protectors are typically fuses or circuit breakers that detect an excess amount of current, which might overheat wiring or devices, and then open the circuit to disconnect power. The most transient ovecommon overvoltages are extremely short duration and termed ‘transient overvoltages,' lasting millionths of a second. These are generally associated with lightning, circuit switching, cycling, etc. (The collective technical community is now embracing the term ‘surge’, but ‘transient overvoltage’ is probably more descriptive terminology. Note that layman understanding of ‘power surge’ may be far different than technical intent, thus causing semantics challenges.) During a transient overvoltage, a surge protector ‘activates’ and redirects harmful surge energy to neutral or ground, then resets itself automatically.

Most surge protective devices (SPDs) include internal suppression elements that operate by varying impedance. These are electrically connected in parallel with the load. During normal operation, the surge protector sits at high impedance and awaits an overvoltage. The high impedance prevents current flow. Upon sensing an overvoltage, the surge protector greatly reduces its impedance, thus allowing the overvoltage to pass through the surge protector as current; thus diverting the surge and protecting the load. Most surge protector failure scenarios involve an ‘in-between’ state where the surge protector has lowered impedance some, but not enough to become a short circuit. There become multiple scenarios of ‘reduced impedance’.

Following are significant regulatory milestones relating to Surge Protectors:

- In August 1998, UL 1449 Second Edition added safety tests that simulated various power system problems believed to damage SPDs. This included controlled SPD failures at 5 amperes and below, and a higher-current test to failure, up to 25,000 amperes.
- In 2002, the National Electrical Code (NEC) introduced Article 285 requiring that SPDs include Short Circuit Current Ratings (SCCRs). This triggered additional safety testing above the previous 25,000 ampere rating; sometimes up to 200,000 amperes.

- In February 2007, UL 1449 Second Edition Revision added additional controlled-failure tests from 10 amperes to 1,000 amperes. These tests proved difficult, prompting product changes, defections away from UL, with some manufacturers literally leaving the industry.
- The 2008 NEC Article 285 included changes as a precursor to upcoming UL changes.
- In September 2009, UL 1449 Third Edition became effective. This effectively obsoleted old-school secondary arrestors, created Type ratings, changed performance testing and added Nominal Discharge Current testing. As with previous UL changes, this turned the surge industry upside down.

Advanced Protection Technologies remains an industry leader with an unparalleled history of Surge Protective Device (SPD) safety. APT products meet and exceed applicable UL testing, proudly wearing the UL Mark. Many products include robust, large-block MOVs for better performance and safety, automatic thermal and overcurrent disconnectors, patented TranSafe circuitry, robust NEMA and UL rated enclosures, etc. We intentionally drive surge protectors into failure simulating compounded power-system problems to ensure the safest possible surge protector. Customers are always welcome at our facility and test labs to witness testing.

FCLs are under active development. In 2007, there were at least six national and international projects using magnesium diboride wire or YBCO tape, and two using BSCCO-2212 rods. Countries active in FCL development are Germany, the UK, the USA, Korea and China. In 2007, the US Department of Energy spent $29m on three FCL development projects.

III. FAULT CURRENT LIMITER

Fault-current problems are commonly faced when expanding existing buses. Larger transformers result in higher fault levels, this in turn needs the replacement of existing bus work and switchgear because of changed fault level. 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.

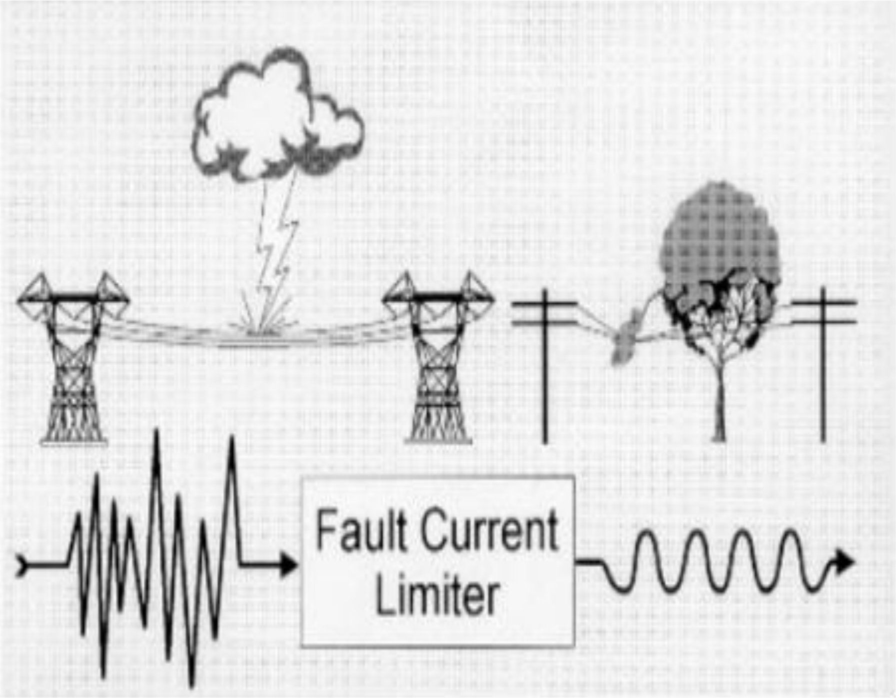


Fig. 5 Desirable attributes of the "ideal" FCL

The attributes of an ideal FCL in the power system may be listed as follows.

- Exhibit zero impedance during normal operation (i.e. no losses, no reactive voltage drop). This requirement is straightforward. It cannot be met completely by real FCL systems but they may come close to the ideal value.
- Provide immediate and "perfect" discrimination between a (temporary) overcurrent situation & a true fault event.

SFCL devices have desirable attributes that make them attractive for grid deployment if their cost and reliability meet acceptable levels. There are also other characteristics that SFCL development teams strive to improve in order to more closely approach the ideal case. In the United States, development teams and the U.S. Department of Energy are developing SFCL prototypes for grid deployment within the next few years.

A. Superconducting technology

The concept of using the superconductors to carry electric power and to limit peak currents has been around since the discovery of superconductors and the realization that they possess highly non-linear properties. The current limiting behaviour depends on their nonlinear response to temperature, current and magnetic field variations.

Increasing any of these three parameters can cause a transition between the superconducting and the normal conducting regime. The curve in the lower half is a normalized plot showing the non-linear relation between current flow in a superconductor and its resistance.

The data for the curve was measured while the superconductor was in a constant magnetic field and a constant temperature. Similar curves can be produced for changes in temperature and magnetic field. The current increase can cause a section of superconductor to become so resistive that the heat generated cannot be removed locally.

This excess heat is transferred along the conductor, causing the temperature of adjacent sections to increase. The combined current and temperature can cause these regions to become normal and also generate heat. The term "quench" is commonly used to describe the propagation of the normal zone through a superconductor. Once initiated, the quench process is often rapid and uncontrolled.

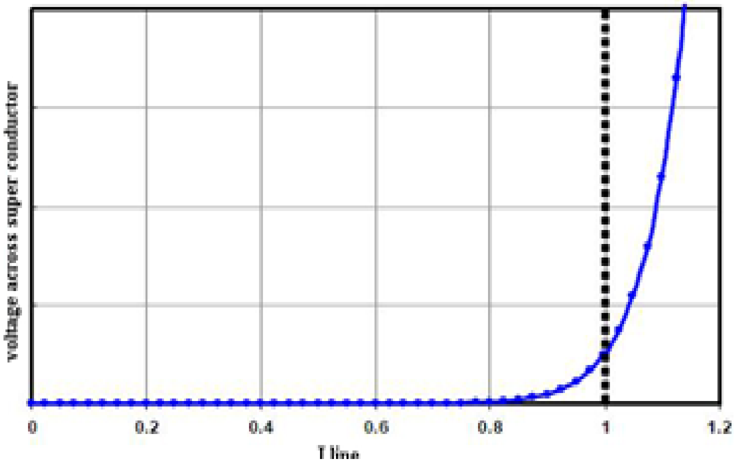


Fig. 6.Voltage-Time characteristics of superconducting technology

Superconducting fault current limiters exploit the extremely rapid loss of superconductivity (called "quenching) above a critical combination of temperature, current density, and magnetic field. In normal operation, current flows through the superconductor without resistance and negligible impedance.

If a fault develops, the superconductor quenches, its resistance rises sharply, and current is diverted to a parallel circuit with the desired higher impedance. Superconducting fault current limiters are described as being in one of two major categories: resistive or inductive.

In a resistive FCL, the current passes directly through the superconductor. When it quenches, the sharp rise in resistance reduces the fault current from what it would otherwise be (the prospective fault current). A resistive FCL can be either DC or AC. If it is AC, then there will be steady power dissipation from AC losses (superconducting hysteresis losses) which must be removed by the cryogenic system. An AC FCL is usually made from wire wound non-inductively; otherwise the inductance of the device would create an extra constant power loss on the system.

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Inductive FCLs come in many variants, but the basic concept is a transformer with a resistive FCL as the secondary. In un-faulted operation, there is no resistance in the secondary and so the inductance of the device is low. A fault current quenches the superconductor, the secondary becomes resistive and the inductance of the whole device rises. The advantage of this design is that there is no heat ingress through current leads into the superconductor, and so the cryogenic power load may be lower. However, the large amount of iron required means that inductive FCLs are much bigger and heavier than resistive FCLs.

IV. WORKING

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. shows.

In Fig, 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 ISC 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.

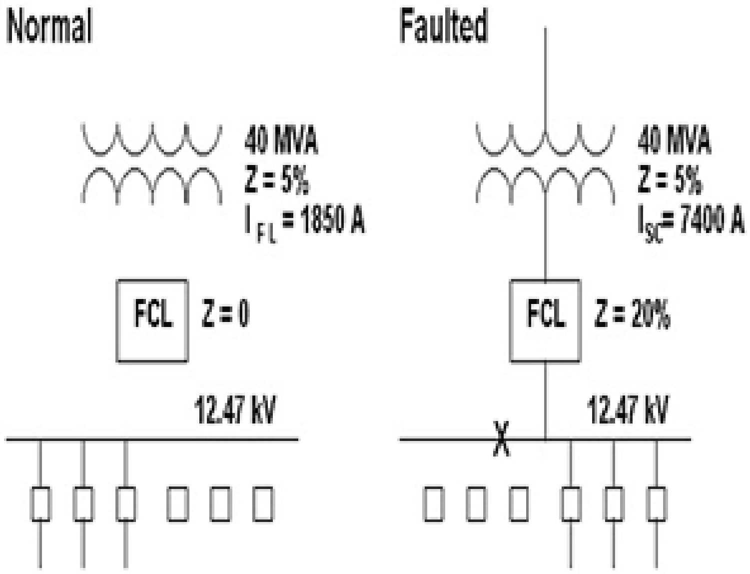

Fig7 Fault control with a fault-current limiter.

Any homeowner knows that surge protectors limit the damaging currents that can harm plugged-in household devices. Simply put, FCLs can provide that same service for electric utilities. These specially designed devices allow for uninterrupted electrical service by limiting and regulating the amount of current moving through the transmission and distribution systems under abnormal conditions.

The emerging technology of FCLs has the potential to save money for utilities and increase efficiency for their customers by protecting equipment from damage and avoiding interruptions and outages. As the demand and sources for electricity rise, utilities are grappling with the challenge of more frequent and larger "fault currents."

B. 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 IFL, the superconductor would be designed to have a critical current of 2IFL or 3IFL. 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 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.

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.

B. 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.yields a limiter suitable for high-current circuits (IL > 1000 A). One phase of the limiter is shown. A copper winding WCu is inserted in the circuit and is coupled to an HTS winding WHTS. 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.

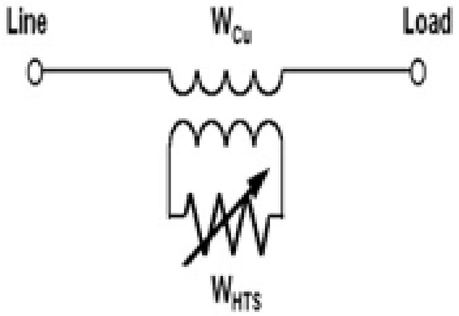

Fig 8. Inductive fault current limiter

50% reduction of fault currents – ¼ cycle reaction time – handles long duration faults and breaker reclosure attempts Fault tolerance is an increasingly important issue in power grid operation .energy Power's Fault Current Limiters protect power grids against damaging power surges caused by short circuits or lightning strikes while maintaining a disruption-free downstream power supply. Inductive Fault Current Limiters provide power grid operators with a new solution for grid reliability, cost-efficient grid expansion, and integration of distributed generation sources.

Energy Power's Fault Current Limiter has been put into regular operation in the United States power grid in March 2009. Southern California Edison is the first electric utility company in the US to use the device for protecting a distribution circuit.

V. APPLICATIONS

Fault-current limiters can be applied in a number of distribution or transmission areas. Three main applications areas are shown in Figs. 9,10,11.

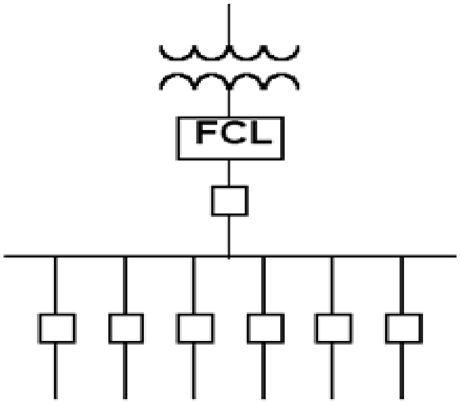

Fig.9 Fault-current limiter in the main position .

The most direct application of a fault-current limiter is in the main position on a bus (Fig. 9). 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
- I2t 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

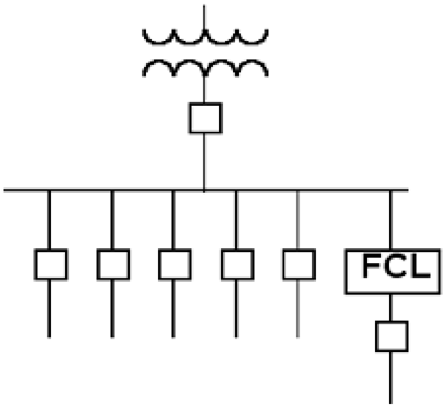

Fig.10 Fault-current limiter in the feeder position .

An FCL can also be used to protect individual loads on the bus (Fig. 10). 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.

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.

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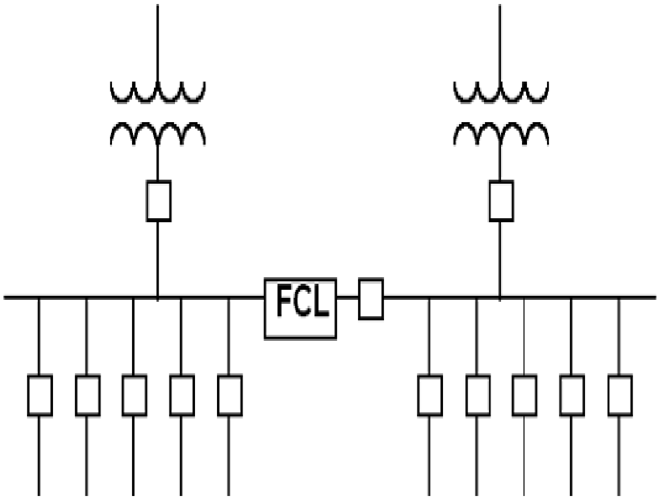

Fig.11 Fault-current limiter in the bus tie position .

An FCL can be used in the bus-tie position (Fig. 11). 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

VI. FUTURE ASPECTS

At present, however, effective superconductors are often expensive and difficult to mass-produce. The Cambridge research could be a step towards resolving this, by providing the basis for the development of more powerful samples that can be manufactured using a commercially compatible process.

That would drive down the production costs of machines that rely on the materials. MRI scanners, for example, which can cost around £1.5million each, could eventually become a common sight in GP's surgeries, helping to improve accurate detection and diagnosis of problems ranging from twisted knees to brain tumours.

In addition, superconductors can act as "fault current limiters" within the national grid, protecting it from the energy surge caused by a sudden rise in consumption. These surges, which caused blackouts across the east coast of the US in 2003 and Europe in 2006, can cause lasting damage to both the grid and public infrastructure. Superconducting materials will cease to conduct without significant energy loss if there is a particularly large current, however, meaning that they can be built into the system to shut down the electricity before it reaches the point of use.

"The potential advantages of developing viable high-temperature superconductors are huge," Professor David Cardwell, head of the bulk superconductivity group at the University's Department of Engineering, where the research took place, said. "The processes we have developed and patented should enable us to develop samples that are better, bigger, cheaper and more reliable."

While some materials need to be cooled down to as low as -269 degrees centigrade to superconduct, YBCO does so at the comparatively "high" temperature of -181 degrees C. This means that it can be cooled with liquid nitrogen, rather than liquid helium, which makes it cheaper to operate.

In the past, however, producing effective bulk superconducting devices from the material has proved difficult. YBCO is processed most easily in the form of a polycrystalline ceramic, but has to be manufactured as a single grain in order to generate large magnetic fields since boundaries between grains limit the flow of current in the bulk sample.

When the material cooled and reformed, these added materials retained their integrity and formed physical obstacles that form direct the motion of magnetic flux lines, enabling larger currents to flow.

VII. CONCLUSION

The recent growth of power circuit capacities has caused fault currents to increase. Since the protection of power systems from the fault currents is very important, it is needed to develop a fault current limiter. A fault current limiter is required to assure rapid reaction to fault currents, how impedance in normal operation and large impedance during fault conditions. A super conducting fault current limiter (SFCL) can meet these requirements superconductors, because of their sharp transition from zero resistance at normal current to finite resistance at higher current densities.

Superconducting fault current limiters exploit the extremely rapid loss of superconductivity (called "quenching”) above a critical combination of temperature, current density, and magnetic field. In normal operation, current flows through the superconductor without resistance and negligible impedance.

Growing electricity demand, the expansion of renewable power and progressive power grid meshing face operators of electric grids with a new challenge: Higher loads, more distributed generation, and changing load flows in the networks lead to increasing fault currents in the event of short circuits. This trend will require substantial spending for replacements of transformers and switchgear in stretched sections of the power distribution infrastructure where fault current levels threaten to exceed the rating of operating equipment in place.

The Superconducting Fault Current Limiter (SFCL) launched by Nexans is a fundamentally new self-acting system that protects grid operating equipment from damaging current peaks during faults events and circuit feedbacks. The SFCL can be deployed to facilitate grid expansion and avert ahead-of-schedule upgrading. It also enables cost-efficient grid stabilization and optimization.

From all discussions in this article, we can see superconducting fault current limiter technology is a very much cost effective, clean, safe, reliable method of fault current limiting. Many researches are going on this topic. It has a very good future scope. In recent decades, all our systems will be of superconducting technology. It is one of the contributing components of smart grid technology. Only the limitation they are facing is that they cannot use for high voltages. Research studies are going on to overcome this difficulty.

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