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Superconductivity Application in Power System

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1. Introduction

Electric power system is one of the most important infra-structure of modern digital society. This energy, which is easy to control, to be converted any type of energy, and clean, is becoming the standard how the society is developed well and the demand of electricity is increasing rapidly over the world.

However, in most highly developed electrical power system, there are several difficulties related from generation to distribution. Usually, power generation is located remote area from the load center, long transmission and distribution lines have to be constructed and maintained to meet required reliability, power quality and economic point of views. Reliable, cheap, efficient conductor is required to support desirable electric power systems.

Most of conductors used in modern power system facilities, for example, generator, transformer, transmission line, cable, motor etc., are copper or aluminum. They have resistance R which restricts the capability of thermal rating of electric facilities with the ohmic loss. If there is a conductor with no loss, we can make efficient electrical facilities. Superconductor, which is zero resistance, is a promising solution to make innovation on electric facilities.

This chapter introduces various power system facilities based on superconductor application. First of all, superconducting cable is most applicable solution to solve transmission congestion problem in high power density area such as metropolitan cities with its high density transmission capability. Recently developed superconducting cable in distribution class can deliver about 5 times more power than conventional XLPE cable at same dimension. DC superconducting cable is also in developing stage to eliminate AC loss in superconductor, and will be applied to HVDC transmission system. Section 2 introduces superconducting cable in power system.

Second promising one is Superconducting Fault Current Limiter (SFCL). With the development of power system, short circuit fault currents are increasing much more than conventional power system which is the components of present system. For example, a lot of circuit breakers have to be replaced higher level break capacity in case of source impedance is reduced by increased power system generation and/or reinforced transmission and distribution system.

SFCL can limit fault current fast, within $1/2$ cycle, using quench effect of superconductor in case of current exceeds specified fault current. Also, it can supply a solution on power system voltage sag problem. Section 3 introduces various type of SFCL and their application.

Other promising applications in power system are Superconducting Synchronous Condenser (DSC : SuperVar) and Superconducting motor. SuperVar is a good solution as

reactive power compensator which can be applied to increase power transmission capability on voltage stability limited system. Also, it can support industry sector which require high voltage quality service. Section 4 introduces SuperVar and superconducting motor with their application.

There are a lot of superconductor application field in power system. However, the basic discussion has to be start with the study whether the power system requirements can have better solution from superconducting electric facilities. In this discussion, we will present to supply some examples how to consider superconducting facilities on modern electric power system. Lastly, we will discuss how to apply superconducting facilities to electric power system.

2. Superconducting cable

Traditionally, the main stream of power delivery system are composed by ACSR(Aluminum Cable Steel Reinforced) in overhead line and XLPE(Cross Link Poly Ethylene) underground cable. In modern highly industrialized society, which requires much higher capacity in transmission and distribution line with the increase of electricity consumption due to energy transition to electricity and population convergence into metropolitan area. However, it is almost impossible to build new power delivery system in metropolitan area in environmental point of view.

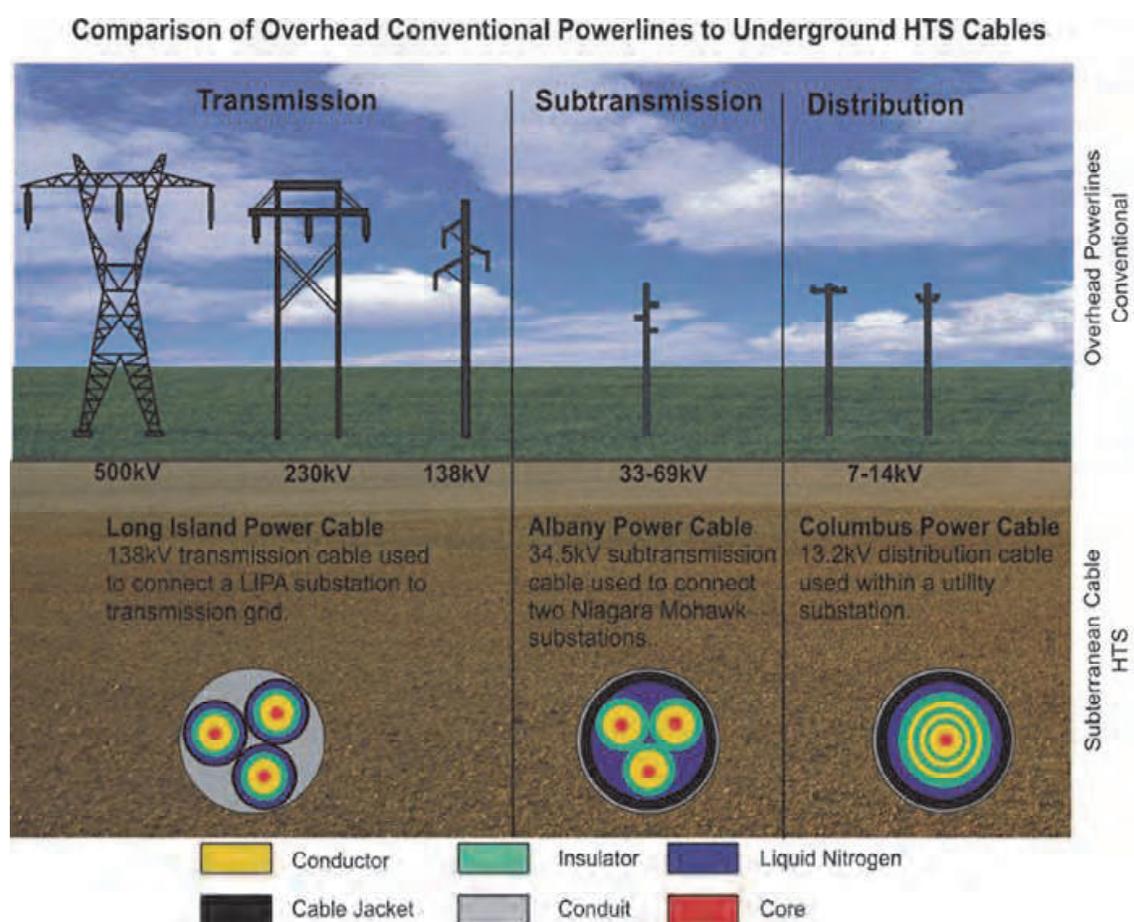


Fig. 1. Comparison of overhead power lines to HTS cable (<http://www.DoE.gov>)

Since superconducting phenomenon was developed by Kamerling Onnes in 1911, research and development on superconducting material has been progressed actively over the world. After McFee suggested superconducting cable at first in 1961, R&D on low temperature superconducting(LTS) cable using Helium cooling system had been studied during 1970's and 1980's.

In 1986, high temperature superconducting(HTS) material which use liquid Nitrogen(LN) instead of Helium had developed by Bednorz and Muller, research on HTS cable has been progressed continuously, and is in industrial application stage at present[1 ~ 3]. Several leading countries, including USA, China, Japan, Europe and Korea already experienced HTS(High Temperature Superconducting) cable test operation[], and finding good applicable places in engineering point of view.

HTS superconducting cable, which has zero resistance and low inductance, can increase power transfer capacity about 3~5 times more than conventional XLPE cable with the same size of underground right of way, and can reduce power transmission loss and construction cost. By DoE, USA, three level of HTS cable is compared to substitute the overhead lines.

Below figure shows the relative power increase compare HTS cable to XLPE cable.

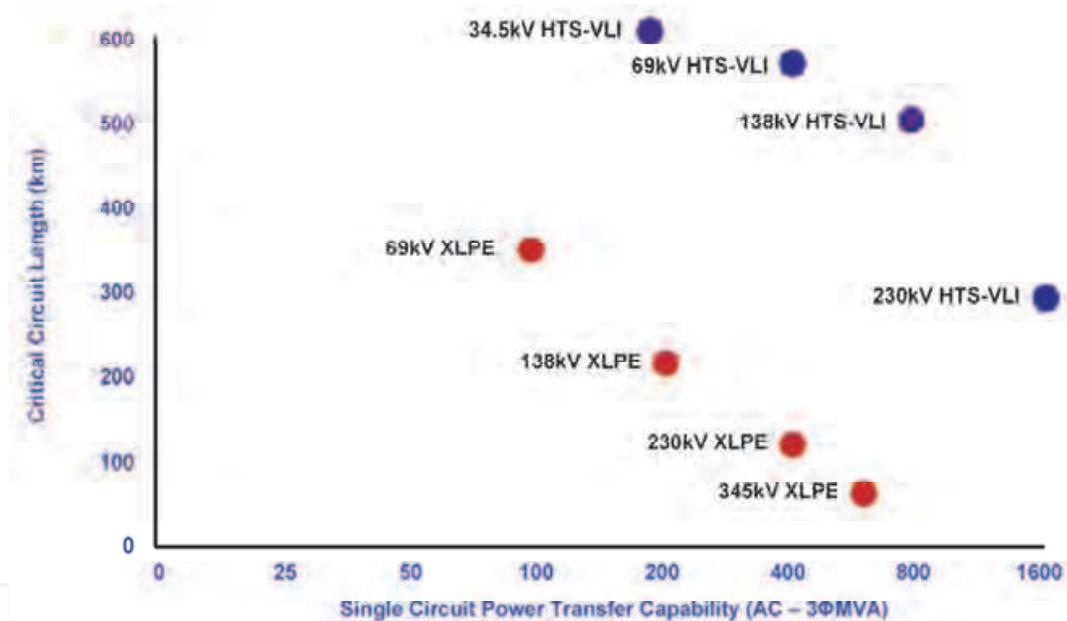


Fig. 2. Comparison of conventional cable to HTS cable

2.1 Type classification

Superconducting cables are classified various point of view. By the electrical source, it is classified AC and DC. Also, by the superconductor material, it is classified HTS(High Temperature Superconductor) which is non-metal, Oxide compound substances such as BSCCO seires and LTS(Low Temperature Superconductor) which is mainly metal seires, such as NbTi.

LTS is cooled by liquid Helium because it has superconducting property nearly absolute temperature(-273.16°C). It is very hard to get near absolute temperature with normal materials and cooling system. Also, Liquid Helium is too expensive to normal use. LTS is easy to make conductor with its ductility, but operation in near zero absolute temperature is very difficult to be utilized in industrial field, such as power transmission system.

However, HTS is cooled by liquid Nitrogen[LN₂] as it has superconducting property about 70[K], temperature gradient between HTS and normal room temperature are much more reduced than LTS case, it makes easier to design cooling system for HTS cable. HTS conductors are more difficult to manufacture and handle as its plasticity is worse than LTS, however it is recognized as cost effective measure compare to LTS as power cable application.

At present, LTS conductors are used for special application such as MRI(magnetic resonance imaging) system. Therefore, our discussion on power cable will focus on HTS cable, later.

HTS cable for power transmission is developed two types of design. The one is WD(Warm Dielectric Design), the other is CD(Cold dielectric coaxial Design).

Fig. 3 (a) shows the cross section of WD HTS cable. LN₂ flows in the tube type former which sustains HTS cable on its outer circle. HTS conductors are surrounded by cryostat which insulates heat transfer. The dielectric is located outer of the cryostat. Therefore the dielectric does not to be cooled with LN₂(Warm Dielectric). Because WD type HTS cable can not only preserve conventional cable dimension and use proved dielectric materials, but also limited HTS conductors are used(omit HTS shield), it is cost effective and efficient in design of cooling system. However, omitting shield layer produces magnetic interaction between phase to phase and limit power transfer capacity.

However, in fig 3 (b) which is the cross section of CD HTS cable, LN₂ flows the outer and inner duct of cable and it cools not only HTS conductor but also dielectric material. Another important difference between CD and WD is that CD has return HTS screening conductors which shields outer magnetics and make low inductance.

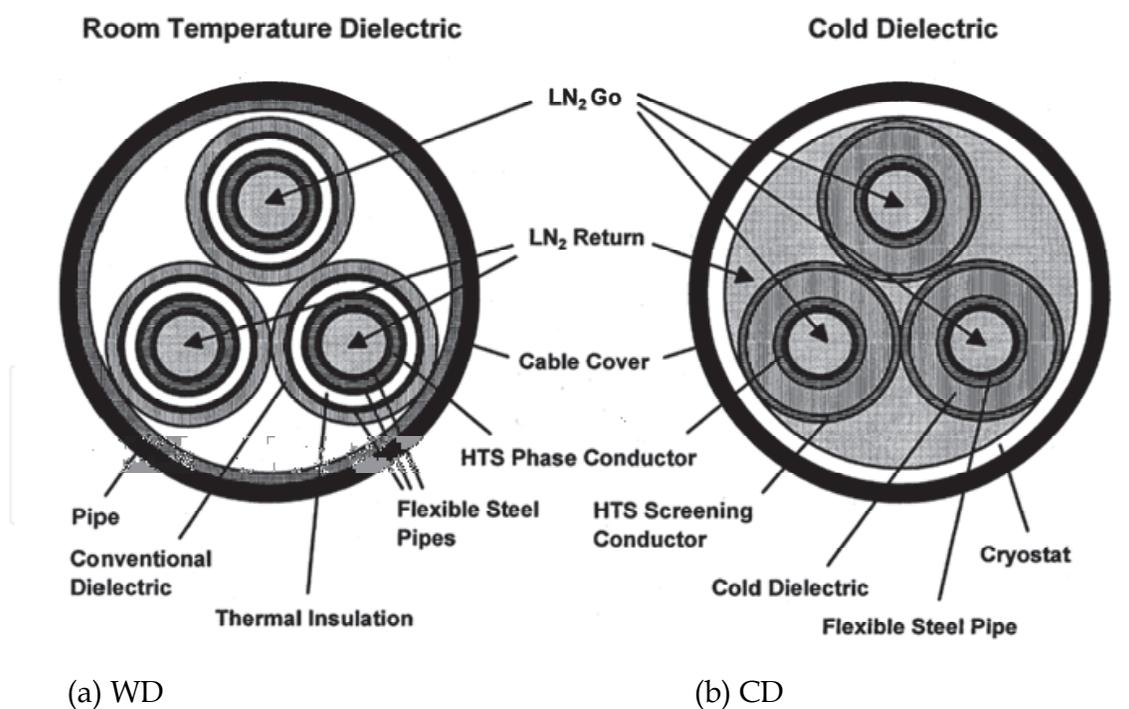


Fig. 3. WD and CD HTS cable

2.2 HTS cable system

General conceptual diagram of HTS cable system is shown as below. The main components of HTS cable system are HTS cable, cooling facility, terminal and monitoring system.

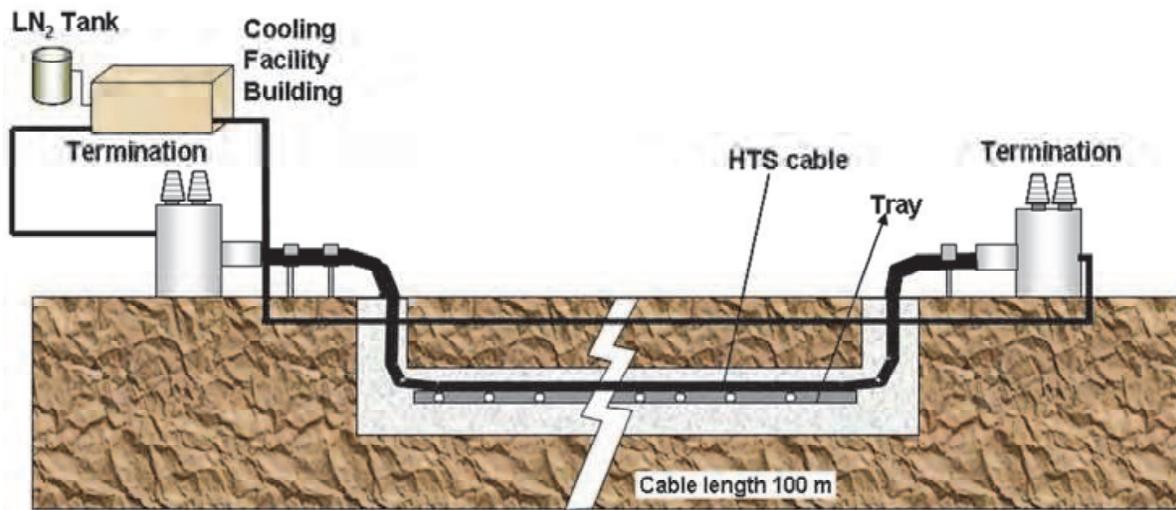


Fig. 4. General conceptual diagram of HTS cable system

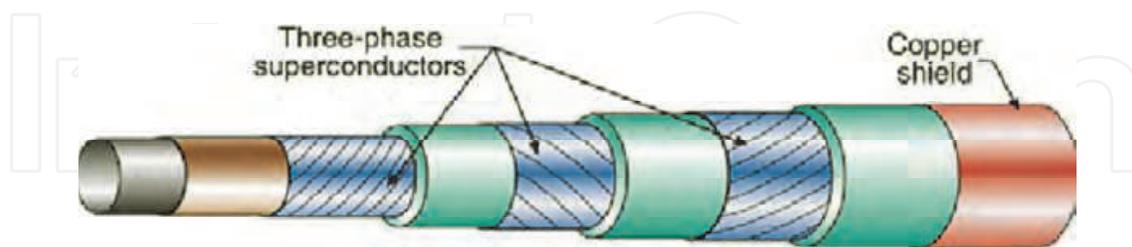
2.2.1 HTS cable

Three kinds of HTS cable in outward appearance are developed. Fig 5 shows single core cable, co-axial core cable, tri-axial cable.



(a) Single core cable

(b) tri-axial cable



(c) Co-axial cable

Fig. 5. HTS cable type classified by core

Usually, single core type is for transmission, tri-axial type is for subtransmission and co-axial type is distribution.

The performance of HTS cable depends on the quality of HTS tape. HTS tape for power cable has to be produced long enough to fulfill the required length of cable core to be

installed, also have sufficient critical current density and uniform current and good mechanical characteristics.

Recently, the improvement of critical current and length in Bismuth series high temperature superconducting wire make possible to realize HTS power cable application in real field. BSCCO-2223, the recently developed HTS conductor which has almost 110[K] critical temperature, is mainly applied to make HTS cable.

Fig. 6 shows CD type HTS cable cross section. It is composed with Former(copper), conductor(HTS), Electrical Insulation(PPLP), electrical shielding(HTS), stainless sheath for thermal insulation and cladding material.

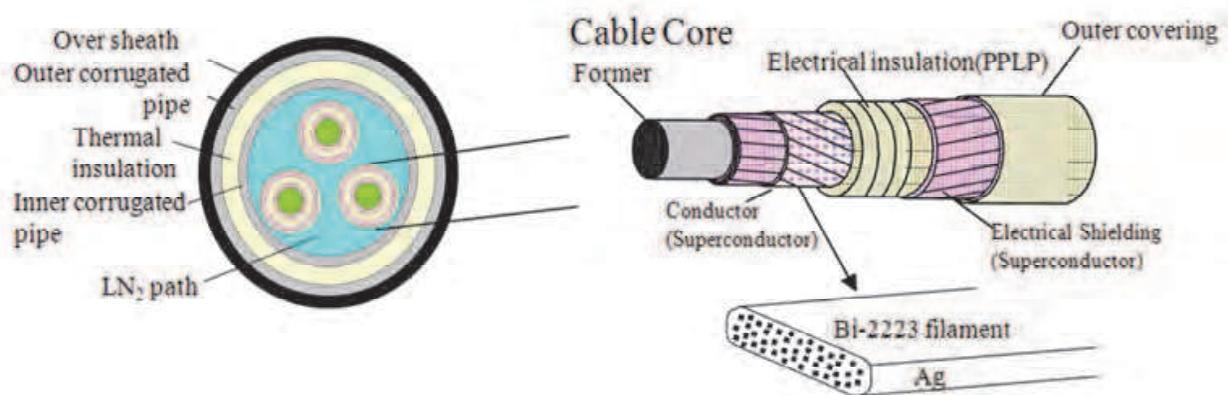


Fig. 6. Cross section of HTS cable(CD type, for distribution system)

Table 2 shows one of HTS cable specification for 22.9kV distribution line. It is designed for replace present distribution cable system without changing underground right of way.

Item	Specification
Former	Stranded copper
Conductor	Bi-2223, 2 layer
Shield layer	Bi-2223, 1 layer
Electrical insulation	PPLP, 4.5 mm
Cable core diameter	35 mm
Superconductor/shield	Bi-2223 tape
Thermal insulation	Double corrugated pipe, MLI, Vacuum
Oversheath	PE
Cable outer diameter	130 mm

Table 1. Example of HTS cable specifications (CD type, for distribution system)

2.2.2 Cooling facility

Cooling facility is another important component of HTS cable system to maintain superconductivity with sufficient low temperature at various operating conditions. In fig.7, LN2 flows LN2 line, superconducting cable, refrigerator and pump. Cryostat prevents heat transfer from cable inner and outer.

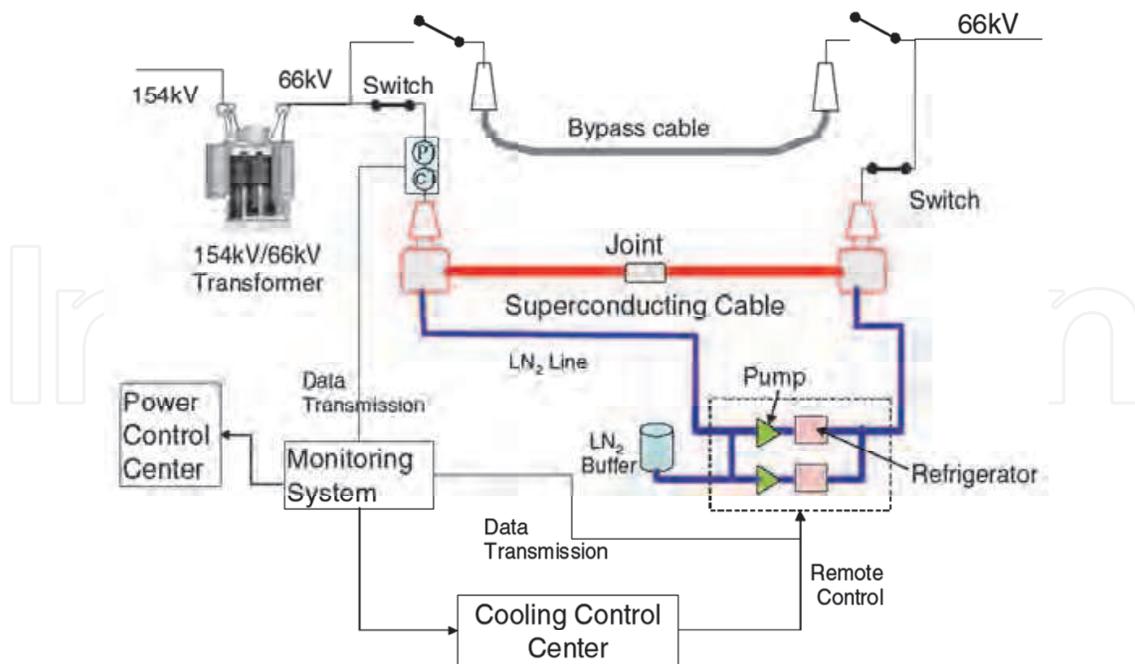


Fig. 7. HTS cable system at Albany project

2.2.3 Termination

Termination locates both ends of HTS cable. It connects HTS cable and normal temperature power line. Because of large difference of temperature between HTS cable and outer weather, termination has to sustain temperature difference and pump out heat from joint resistance.

2.2.4 Monitoring system

Monitoring system checks electrical and thermal status of HTS cable system. Electrical variables are currents and voltages. Thermal variables are temperatures of every components, such as cable inlet, outlet, refrigerator inlet and outlet etc.

2.3 Characteristics of HTS cable

2.3.1 Electrical characteristics

Brief comparison of electric characteristics among power delivery systems are suggested in table 2.

WD type can transfer about 2 times power than conventional cable at same power loss, however, CD type can transfer about 4.5 times power. Below table shows brief comparison between WD and CD type.

	conventional	HTS(WD)	HTS(CD)
Pipe outer diameter(mm)	200	200	200
Voltage(KV)	115	115	115
Power rating(MVA)	220	500	1000
power loss(W/MVA)	300	300	200

Table 2. Comparison of ratings between WD and CD HTS power cable

The capacity of WD HTS cable is about 2.5[kA] per phase at 132/150~400[kV] transmission voltage and 500~2000[MVA] per system[2]. CD type has better current capacity than WD type, 8[kA]/phase. Also, DC HTS cable can transfer 15[kA] and more at same design.

Power delivery system	Cable dimension			Electrical constants(Z_1 / Z_0)		
	Inside Radius [mm]	Outside Radius [mm]	Shield Radius [mm]	Resistance [Ω /km]	Inductance [mH/km]	Capacitance [nF/km]
Conventional XLPE	2	25	40	0.03/0.15	0.36/1.40	257/175
HTS WD type	12.7	14	29	0.0001/0.12	0.39/1.47	217/175
HTS CD type(VLI)	12.7	14	29	0.0001/0.03	0.06/0.10	200/140

Table 3. Comparison of electrical constants between WD and CD HTS power Cable

Table 3 introduces the electrical constants of HTS cable. We can find that CD type cable has only 1/6 positive sequence inductance over WD and XLPE cable which acts as impedance in AC system. This tells us CD type HTS cable shows excellent power transfer capability at steady state.

However, it has quench property if the conductor temperature rise over critical temperature, the resistivity increase dramatically. See Fig.8.

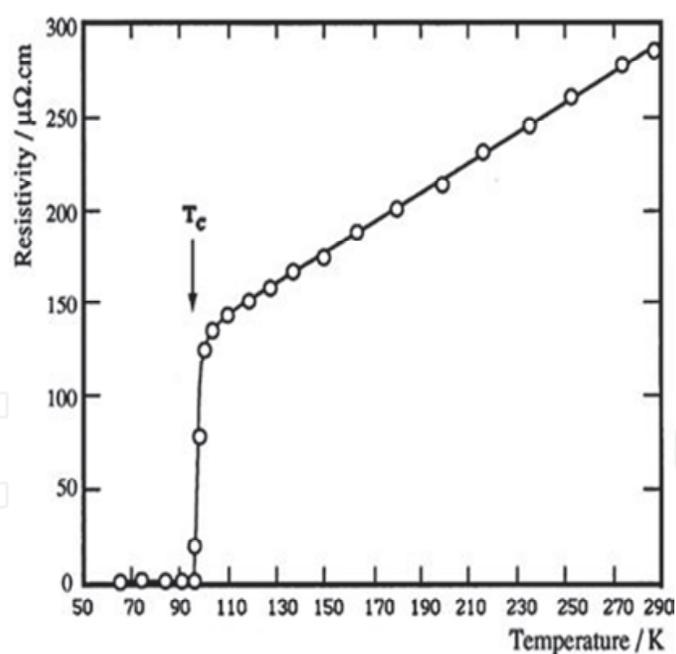


Fig. 8. Temperature and Resistivity of HTS conductor

2.3.2 Thermal characteristics

To sustain superconductivity of HTS cable in normal operation, it is very important to keep the temperature of cable system within permissible range. Depend on above figure, if temperature rise over about 97[K], quench happens.

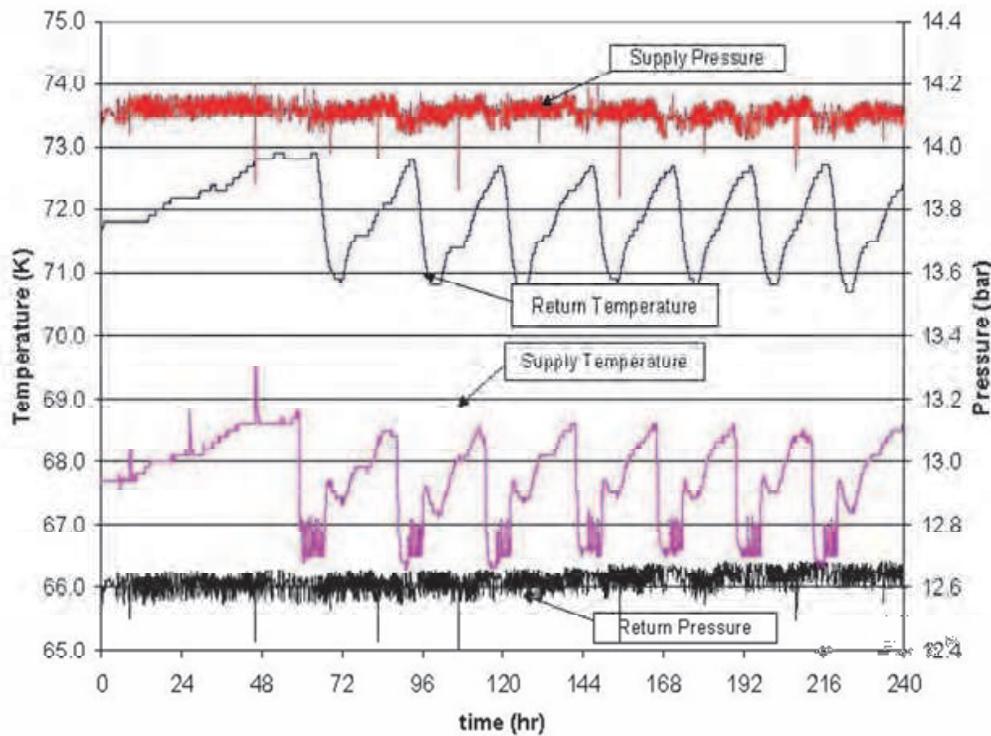


Fig. 9. Inlet and outlet temperature of HTS cable

Above figure shows the temperatures of inlet and outlet of HTS cable during load cycling operation. At both terminal, temperatures are below 73[K] and there are about 24 degrees temperature margin.

2.3.3 Operational characteristics of HTS cable system in sample system

In this section, a sample of distribution level HTS cable operation status shall be introduced to understand each electrical components response to steady and transient state. HTS cable may be operated at unbalanced 3 phase currents, harmonics, various fault condition. Well designed HTS system has to survive expected abnormal state.

2.3.3.1 Sample system

22.9kV, 50MVA distribution CD type HTS cable applied sample system is introduced in Fig.8 and Table 4.

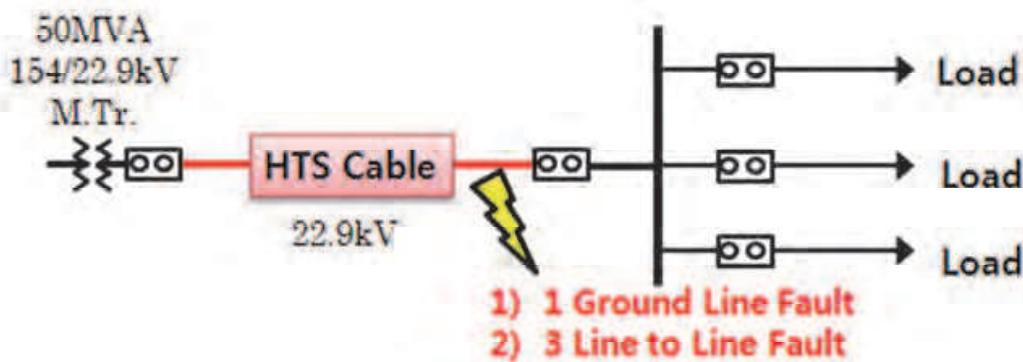


Fig. 8. Model distribution system

Items	Specification
Rated Voltage	22.9 kV
Rated Current	1,250 A
Capacity	50 MVA
Length	100 m
Cable Type	3 cores in one cryostat
Dielectric Type	Cold dielectric
Cable Size	Applicable for 175 mm duct
Response to Fault Current	There shall be no damage for the cable and cable system when the fault of 25kA is applied to the cable for 5 cycles.

Table 4. Ratings of modeled HTS cable

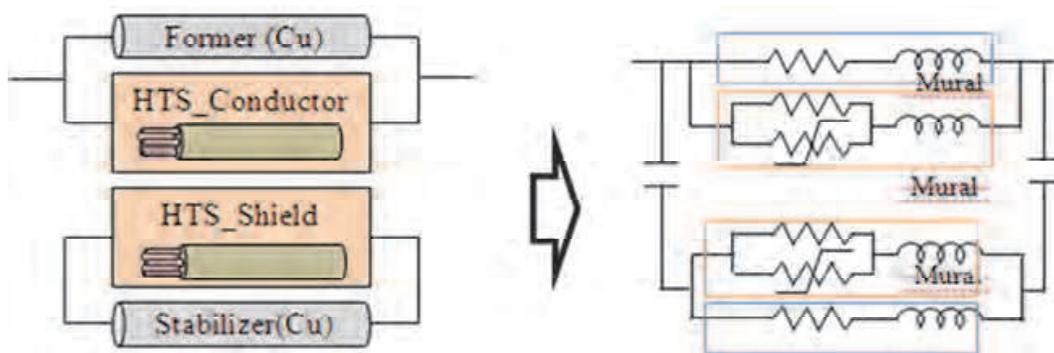


Fig. 9. CD type HTS cable modeling

To verify electrical characteristic more detail, each conductors and formers are modeled with EMTDC and compared with test results.

2.3.3.2 Normal operation characteristics -3 phase balanced case

When the operating current of HTS cable increased up to 2/3 of rated current, the conductor and shield current are measured[Fig 10]

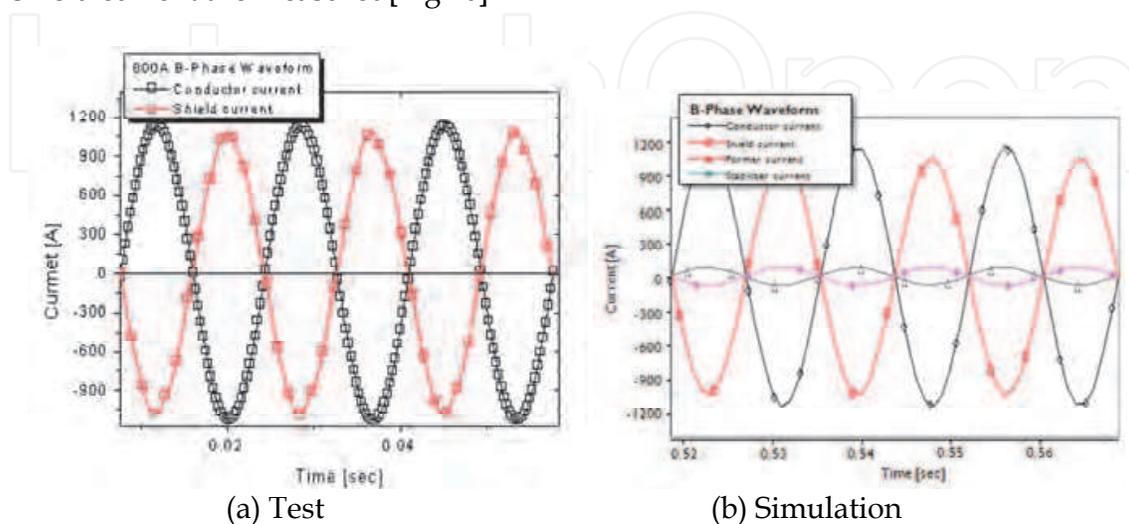


Fig. 10. Test and simulation results (Balanced case 800Arms: conductor and shield current)

In a) and b), currents in conductor and shield are almost same and opposite phase. Errors of measured and simulated value are 1.7%(HTS conductor) and 0.7%(Shield), respectively. This errors are regarded as heat characteristics and AC loss effects of HTS cable.

Abnormal operation characteristics – 3 phase unbalanced case

Fig. represents the test and simulation results of 30% unbalanced case. Errors between test and simulation reaches 6.5% maximum.

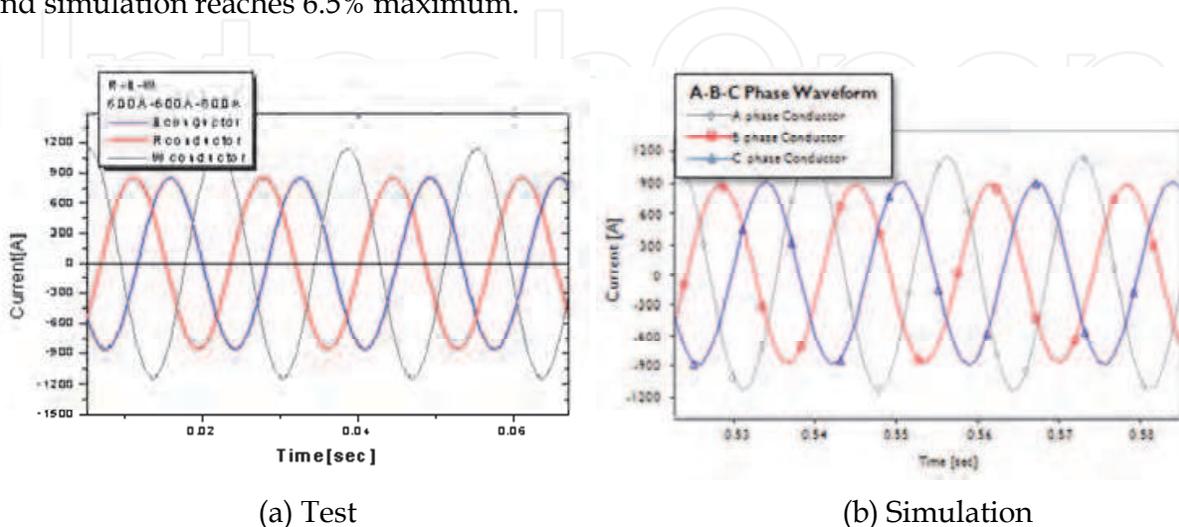


Fig. 11. Test and simulation results (Unbalanced case 600/600/800Arms: conductor and shield current)

2.3.3.3 Abnormal operation characteristics – harmonics

Harmonics can increase AC loss of HTS cable due to hysteresis loss. Hysteresis loss model is as below equation.

$$P_{HY} = 2\pi n \eta V B_{max}^n = k B_{max}^n \text{ [W/m}^3\text{]} \tag{1}$$

- f : frequency [Hz]
- B : flux density[Wb/m²]
- n : exponential index on material [2.1]
- V : volumn of material
- k : total constant

In case of high THD, especially higher order harmonics are included dominantly, the hysteresis loss will be increased because it is proportional to frequency. Regarding harmonics, HTS cable system has to increase cooling capacity and/or decrease operating capacity of HTS cable.

2.3.3.4 Abnormal operation characteristics-fault currents and thermal characteristics

In abnormal operation status such as short circuit current passing condition, superconducting cable has to pass large current securely. Usually, fault current rises 10 times more than normal current, this excessive current may over critical current (I_c) of superconductor. In this case, current quench may happen and very rapid temperature rise may take place and the HTS cable may be damaged . Therefore, various methods such as fast circuit breaker and/or parallel conductor(copper former) are applied to protect quench of HTS conductor.

In CD type HTS cable, most of fault currents are transferred from HTS conductor to former conductor because of superconductor resistance rise. When temperature is supposed as constant, HTS conductor resistance is calculated by next equation.

$$R_{HTS} = \frac{V_{HTS}}{I_{HTS}} = r_c \times \left(\frac{I_{HTS}}{I_{c,HTS}} \right)^{n-1} \quad (1)$$

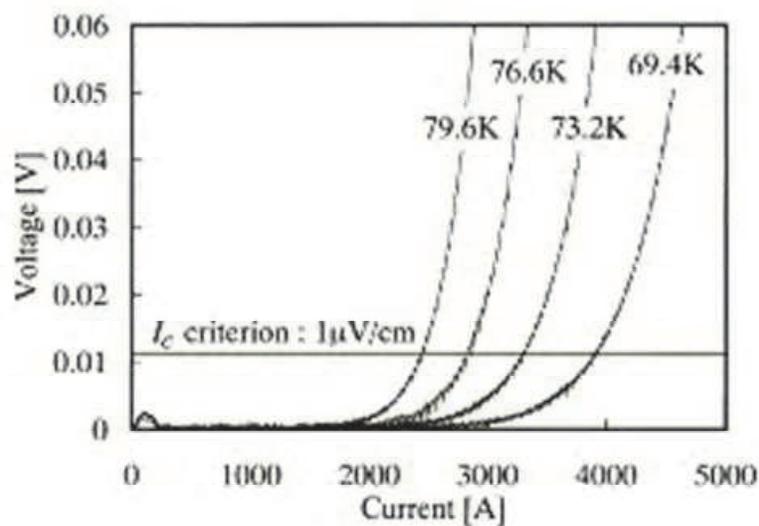


Fig. 12. V-I curve of 66kV HTS cable

During fault current, the internal heat dynamics can be approximately formulated by heat insulated equation because electric dynamics ends within very short time (0.1 seconds) compare to heat dynamics.

Therefore, quench dynamics are represented next heat balance differential equation.

$$C(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + Q(T) - W(T) \quad (2)$$

$C(T)$: heat capacity

The left side represent temperature rising rate of HTS cable, the first term of right side represent heat transfer to superconductor, and $k(T)$ is heat transfer rate, $Q(T)$ is internal heat generation due to current, $W(T)$ is cooling heat.

Therefore,

$$Q(T) = \frac{\rho(T)}{A} I(t)^2 \quad (3)$$

$I(t)$ is current, ρ is resistivity of tape, A is cross section area.

If we suppose fault current flows within very short time, heat transfer and cooling effect can be disregarded. Therefore, equation (2) simplified as (4).

$$\int_{t_b}^t \frac{\rho_{AR}(T)}{A_{AR}} I^2 dt = \int_{T_b}^T m_{HTS} c_{p,HTS}(T) dT \quad (4)$$

In quench state, voltage of quench area will be increase and cable impedance(R+jX) is increased too.

Every nonconductors in cable acts heat resistances of heat tranfer. The heat resistance of each insulation can be calculated as follows.

$$T = \frac{\rho_{th}}{2\pi} \ln\left(\frac{r_2}{r_1}\right) \tag{5}$$

T : Heat resistance of each insulation layer in unit length [K·m/W].

ρ_{th} : heat resistance of material

r_1, r_2 : inner and outer radius of insulator

Most of problem related cable rating is determined by passed time and modeled by heat balance equation. However, solving it is very difficult with numerical analysis. Therefore, in most calculation case, we define heat capacity of cable as equation (6) and use simple approach.

$$Q = V \cdot c \tag{6}$$

V = cable volumn[m³]

c = heat capacity of material [J/m³°C]

Next Figure represents and example of heat equivalent circuit between conductor and sheath of cable. Qc represents heat capacity of conductor and sheath. Heat capacity of dielectrics are calculated.

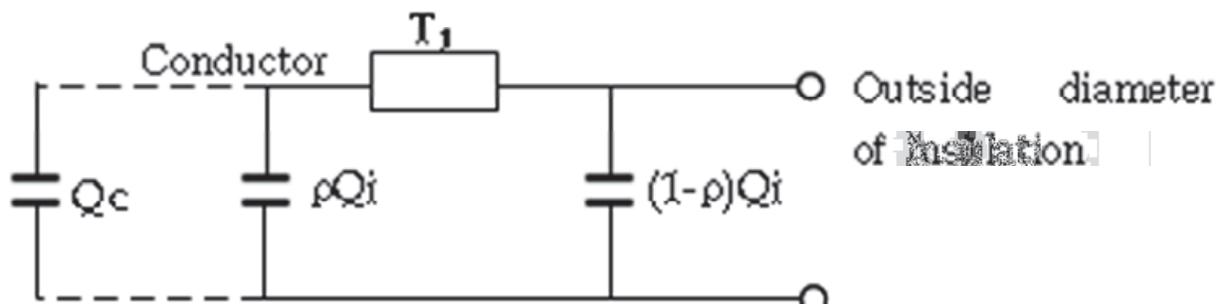


Fig. 13. Equivalent heat transfer circuit of HTS cable

T₁ : Total heat resistance of dielectric material

Q_i : Total heat capacity of dielectric material

Q_c : heat capacity of conductor

heat capacity coefficient ρ can be calculated equation (7)

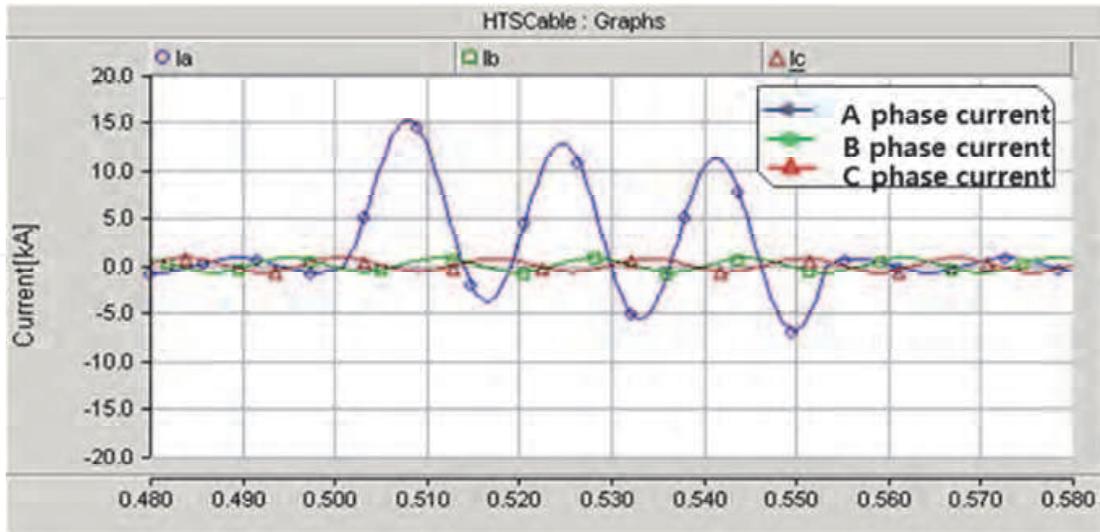
$$\rho = \frac{1}{2\ln\left(\frac{D_i}{d_c}\right)} - \frac{1}{\left(\frac{D_i}{d_c}\right)^2 - 1} \tag{7}$$

D_i: Cable inner diameter

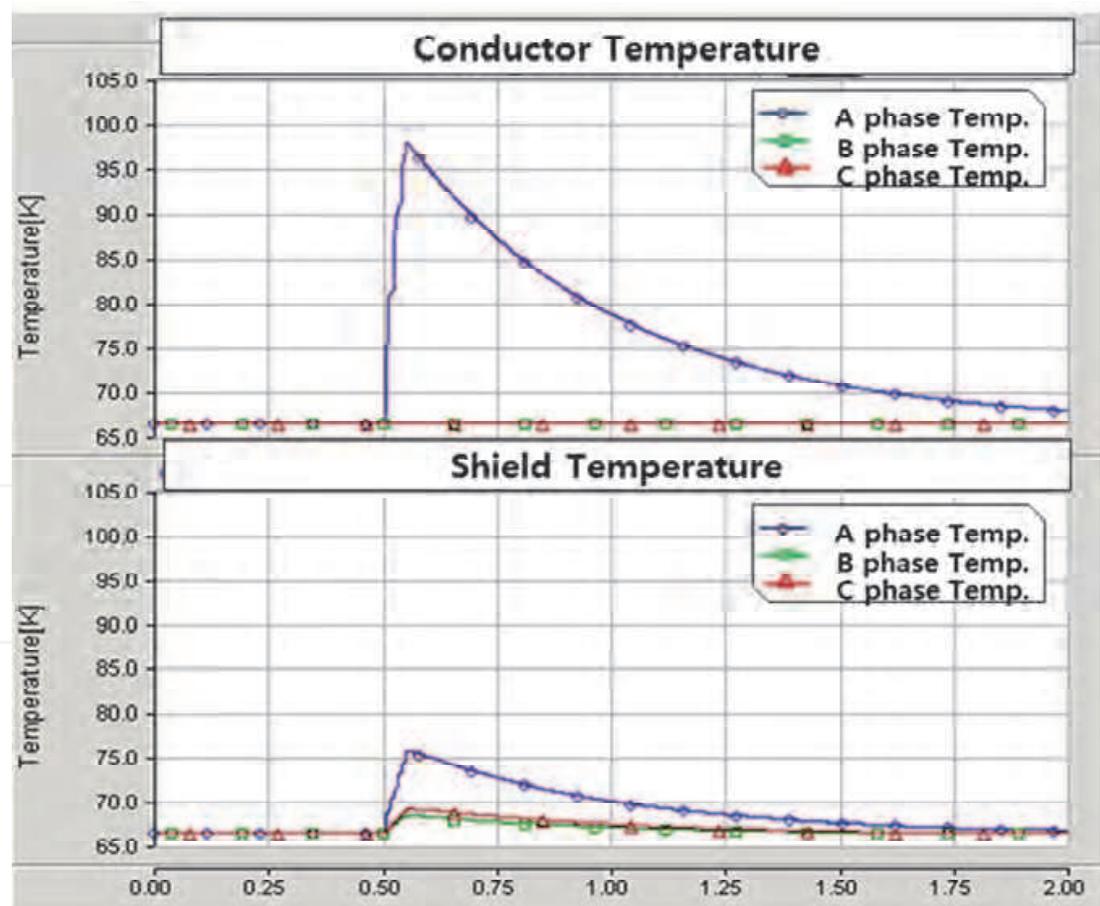
d_c : conductor diameter

2.3.3.5 Fault example - single line fault case

Fig. 14 shows the simulation results of single line to ground fault case on above distribution system



(a)



(b)

Fig. 14. Current and temperature of HTS cable in fault condition(SLG)
 (a) fault current at Single line fault (b) temperature of conductor and shield

With the fault current of A phase, HTS conductor of phase A temperature rises from 67[K] to 97[K] during fault time. If quench temperature is 105[K] normally, there is little margin to this HTS cable system.

3. Superconducting Fault Current Limiter(SFCL)

3.1 Fault Current Limiter and SFCL

In electrical network, there are various faults, such as lightning, short circuits, grounding etc., which occurs large fault current. If these large currents are not properly controlled for power system security, there happens unexpected condition like fire, equipment and facility damage, and even blackout. Therefore, Circuit Breakers are installed and have the duty to cut off fault current, however, it takes minimum breaking time to cut, and sometimes fail to break.

Fault Current Limiter(FCL) is applied to limit very high current in high speed when faults occur. Different with normal reactor, normal impedance is very low and have designed impedance under faulted situation. Fault limiting speed is high enough that it can limit fault current within 1/4 cycle. Also, this function has to be recovered fast and automatically, too.

Various FCLs are developed and some of them are applied in power system. Most typical FCL is to change over circuit from low impedance circuit to high impedance circuit. Circuit breakers and/or power electronics devices are used to control FCL circuits. Fuse or snubber circuits are used to protect high recovery voltage. These FCLs are attractive as it implements normal conductor, however, there are weak points such as slow current limiting speed and big size in distribution and transmission level as well.

Superconducting fault current limiter (SFCL) has been known to provide the most promising solution of limiting the fault current in the power grid. It makes use of the characteristic of superconductor whose resistance is zero within critical temperature (T_c) and critical current (I_c). If fault current exceeds I_c , superconductor lose superconductivity and the resistance increase dramatically (called quench) and limit circuit current.

3.2 Classification of SFCL

Various types of SFCLs have been built and showed desired current limitation up to medium voltages. Some of them were actually field-tested in the electrical power grid. However, the SFCLs seem to be not near to commercial operation in the grid. This means that the SFCL is not ready to satisfy the utilities in various conditions. The conditions are dependent upon the application conditions, general purpose applications and special purpose ones.

We can classify these SFCLs as three types, which are resistance type(R-type), Inductance type (L-type) and saturable core type. R-type makes use of quench resistance of superconductor directly. L-type makes use of superconductor as trigger element for circuit inductance which limits fault current. Saturable core type makes use of superconductor magnet to saturate reactor iron core. In normal operation, this reactor has a little reactance in saturation state. However in fault state, fault current releases saturation state and increases impedance, therefore limits fault current.

3.2.1 R-type and L-type

The conceptual circuit of R-type and L-type SFCL is shown Fig. 15. In SFCL(Limiter), R_p is fault limiting resistance when R-type. In case of L-type, R_p will change as L_p (fault limiting inductance). If i_{ac} reaches critical current, R_{sc} should be quenched and its superconducting

characteristics will be lost (resistance will be increased dramatically) , so fault current will be limited by R_p .

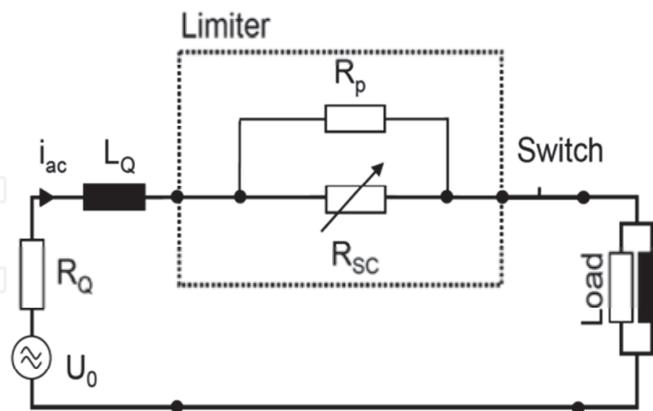


Fig. 15. R-type and L-type SFCL conceptual circuit

The mathematical model of SFCL is expressed as equation (8).

$$Z(t) = Z_s \left[1 - \exp \left(- \frac{t - t_0}{T_s} \right) \right] \quad (8)$$

T_s is time constant of impedance, t_0 is delay time of SFCL, Z_s is impedance of SFCL.

$$Z_s = R_s + jX_s \quad (9)$$

$$R_s : R\text{-Type}$$

$$X_s : L\text{-Type}$$

By the equation (8), impedance dynamics of SFCL is as Fig. 16.

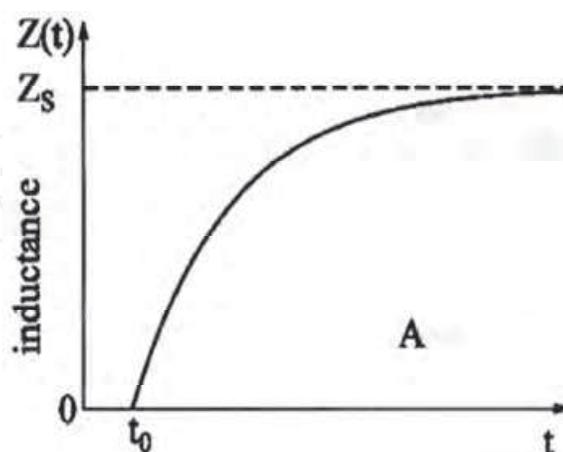


Fig. 16. Characteristics of SFCL impedance

R-type SFCL can limit peak current if proportional to R_s . L-type has slow damping characteristic because of transient DC component. The superconductor resistance value of SFCL (R_{sc}) is dependent to its type, it rise about 25 [pu] exponentially within 1[ms].

3.2.2 Saturable core type

The conceptual circuit diagram of saturable core type SFCL is shown Fig. 17. In normal state, two core fluxes are saturable with currents I_0 . When fault current i_{ac} flows, saturable fluxes are decreased and inductance of L_1 and L_2 increase along with B-H curve.

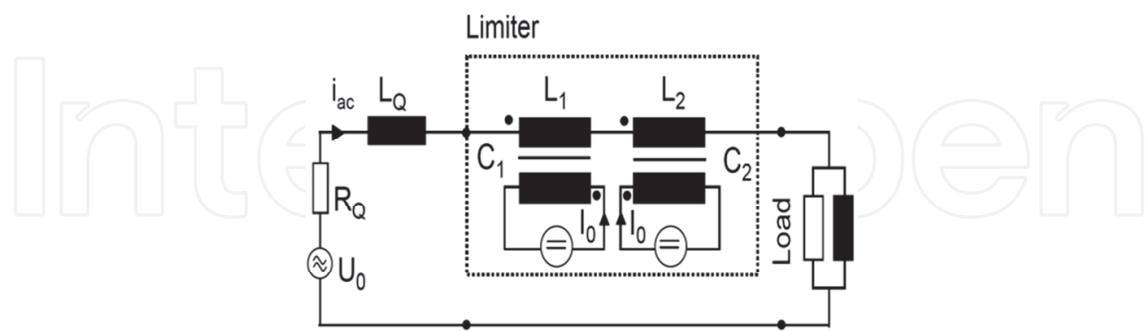


Fig. 17. Saturable core type SFCL conceptual circuit

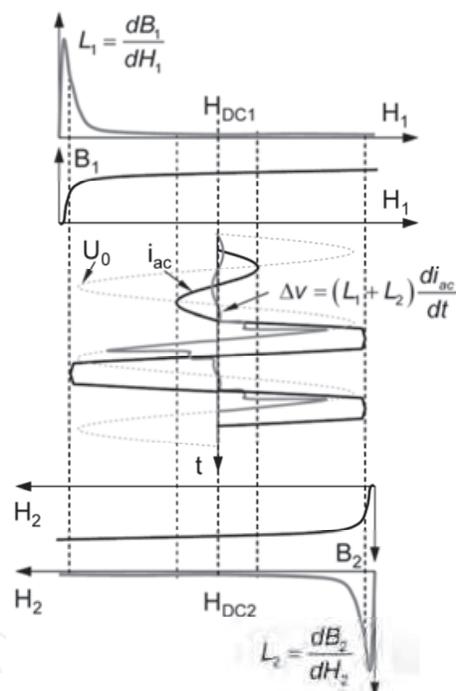


Fig. 18. Saturable core type characteristics

3.2.3 Hybrid type

Currently two types of SFCLs are widely developed at medium and high voltage scale, the resistive type and the saturable iron-core type SFCLs. Since a resistive SFCL component is limited in current and voltage ratings, inevitable is a large number of components to be assembled, so a large cryostat to cool them. Likewise, the saturable iron-core type carries large size iron cores.

To match these requirements, hybrid SFCL is developed for medium voltages class. The hybrid structure is composed of superconducting parts and conventional switches. This resulted in drastic reduction of superconductor volume, followed by smaller cryostat. The

design also provides standing alone current limitation, reclosing capability, and other functions.

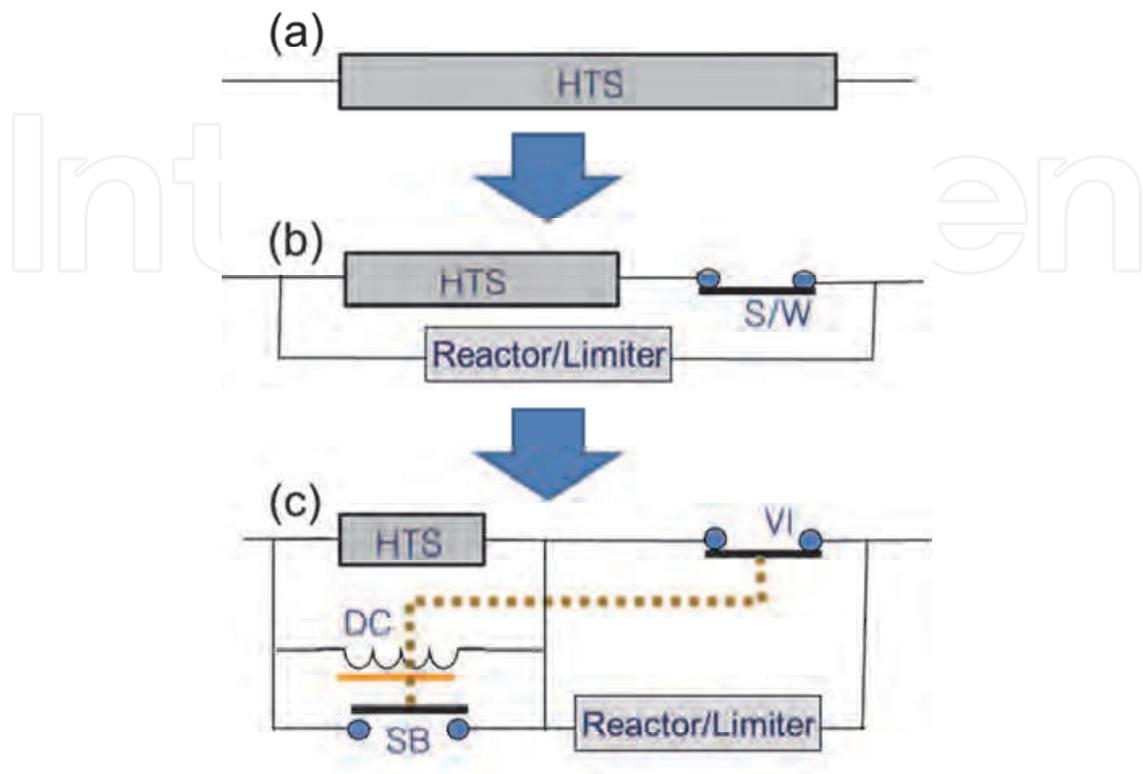


Fig. 19. Design innovation of resistive SFCLs. (a) conventional resistive type, (b) hybrid type with a conventional breaker, (c) hybrid type with a fast switch

3.3 Developed/Applied SFCLs

The first installed one is developed by ABB. After that, various SFCLs are developed for distribution and transmission application to protect bus and/or feeder from high fault currents. Fig. 20 shows recently developed and installed SFCLs for distribution level.

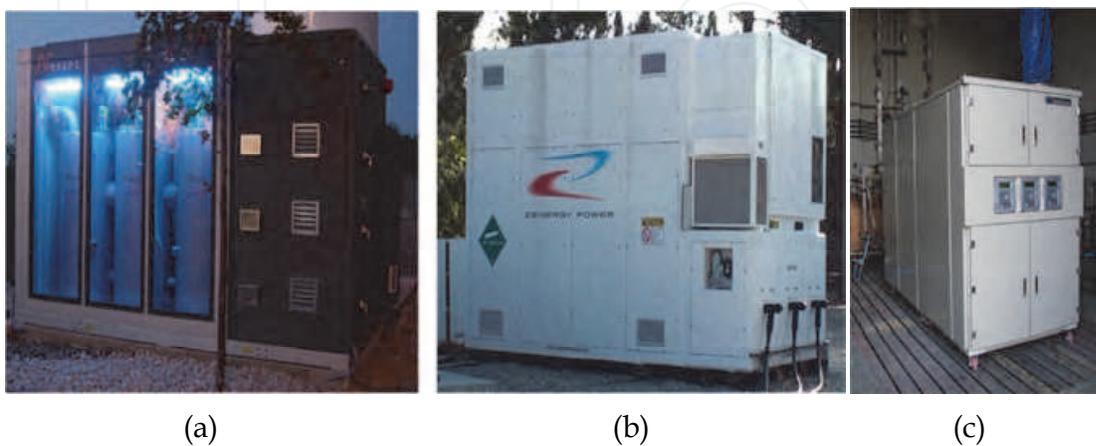


Fig. 20. Distribution class SFCLs, (a) Boxberg, Germany (b) Shandin, USA, (c) Kochang, Korea

place	developer	Voltage (kV)	Type	status
ABB P/P, Swiss	ABB	10.5	R-type	Operated 1997(6month)
Puji S/S, China	Innopower	10.5	Saturable Core	In operation (2008~)
SCE Shandin S/S USA	Zenergy Power	15	Saturable Core	In operation (2009~)
Tokyo Gas, Japan	Toshiba	6.6		In operation (2007~)
Lancashire, U.K	Nexans SC	12	R-type	In operation (2010~)
Boxberg P/P, Germany	Nexans SC	12	R-Type	In operation (2009~)
San Dionigi S/S Italy	CESI RICERCA	9	R-Type	In operation (2011~)
Kochang, Korea	KEPRI/LS	22.9	Hybrid	In operation (2009~)
SCE, USA	AMSC/Siemens	115	R-Type	In operation (2011~)
AEP, USA	ZenergyPower	138	Saturable Core	In operation (2011~)

Table 5. SFCL Developments for Transmission level

3.4 Applications of SFCL

The utilities used to require that the SFCL must be robust, reliable, of low cost, and (almost) maintenance-free for long time use. These would be universal conditions that any SFCL is expected to satisfy. In addition, there may be local conditions associated with the special purpose application of an SFCL by local demands. The local conditions may be specific size, cost, current limitation performance, reclosing capability, and so on.

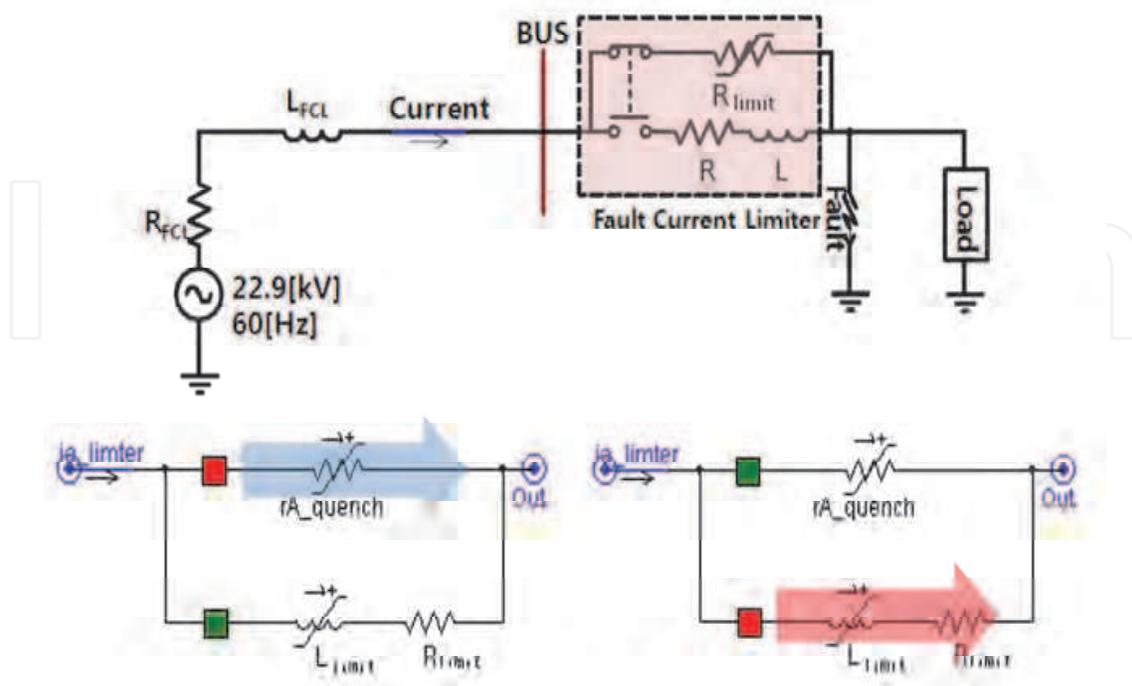


Fig. 21. SFCL sample system

SFCL has many good points, such as small size, faster fault current limiting, little parts, no power increase in fault circuit. Therefore, various applications are expected as follows, for example.

- Increase power transfer flexibility applied to bus-tie between distribution transformers
- Reduce voltage sag applied to sensitive load.
- Reduce ground fault current applied to neutral impedance for transformer

Below is case study result how SFCL is work in 22.9kV distribution system.

variables	L_{limit}	R_{limit}	$rA_{\text{quench}}(\text{normal})$	$rA_{\text{quench}}(\text{fault})$
Value	0.005[H]	1.0[Ω]	0[Ω]	$r_0 \times \left(\frac{I}{I_{\text{crit}}}\right)^{n-1}$

Table 6. Constants of sample SFCL

In this simulation, maximum quench resistance is 5 [Ω]. Fig 22 shows how SFCL limits fault current compare to non-SFCL circuit. The fault current could be reduced dramatically within 1/4 cycle by SFCL.

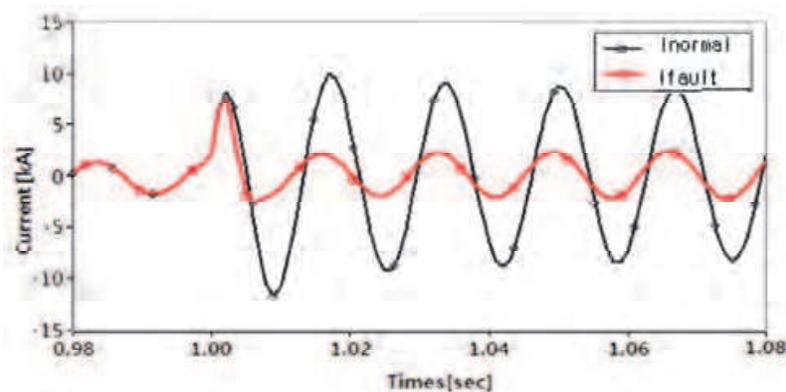


Fig. 22. Simulation result of SFCL dynamics

4. Dynamic Synchronous Condenser (DSC : SuperVar)

Synchronous Condensers (SC) are a good facility to support dynamic reactive power both capacitive and inductive area to improve system voltage characteristics. They are rotating machine rotating in synchronous speed. When we operate a synchronous generator connected power grid without driving motor, it is operated as synchronous condenser.

Its reactive power can be controlled with field current excitation. When overexcited, it generates capacitive reactive power. If under-excited, it generates inductive reactive power.

Today, this machine is not preferred because of high power loss and maintenance problem. Static reactive compensators such as STATCOM (Static Compensator) and/or SVC (Static Var Compensator) are preferred alternatives with rapid response and easy maintenance. However, synchronous condenser has excellent characteristic to support dynamic rating compare to above static compensators.

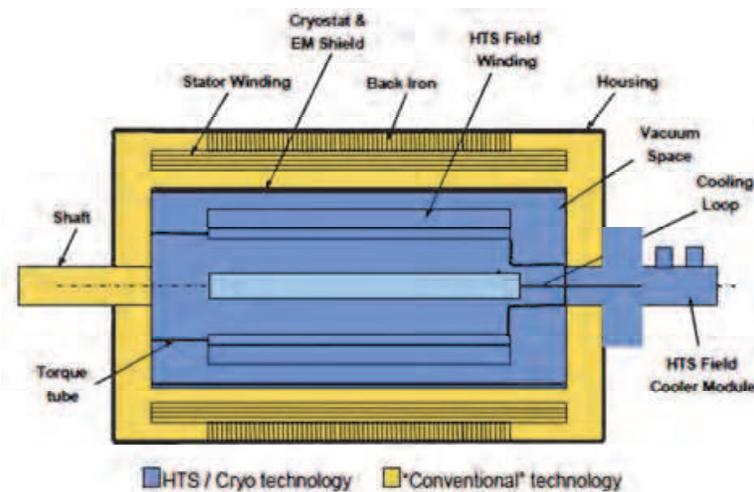
Dynamic Synchronous Condenser (DSC) has upgraded existing SC technology by using a conventional armature mated with a field winding made from High Temperature

Superconducting (HTS) wires. With the upgrading of field magnetic flux density as HTS conductor, it can provide up to 8 [pu] current for short periods to support transient VAR requirements. Key benefits of DSC are as follows:

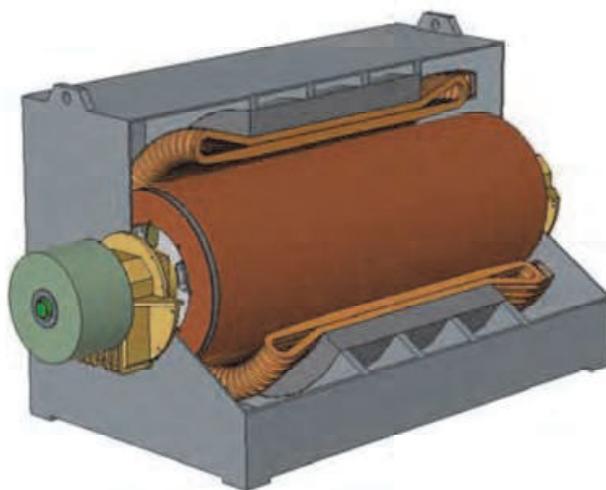
- Fast response to transient voltage variation at both reactive power
- Low losses
- Simple installation (small footprint)
- Low maintenance
- No harmonic generation

4.2 Configuration

The major components of a DSC are shown in Figure 23. The field winding employs HTS conductor which is cooled with a cryocooler to about 35-40K. The cryocooler modules are located in a stationary frame and a fluid such as gaseous helium or liquid neon is employed to cool components on the rotor. The stator winding employs conventional copper windings.



(a)



(b)

Fig. 23. Conceptual diagram of a DSC

(a) superconducting field winding in cryocooler , (b) DSC model picture

4.3 Electric characteristics and performance

The DSC has low synchronous reactance which increases power system stability and reactive power/voltage compensation compare to a conventional SC. The characteristics DSC are summarized below:

- With low synchronous reactance, DSC provides less voltage drop ratio between no-load and full-load operations
- The sub transient reactance (x_d'') of the machine is also low (0.11 pu) which lets the machine provide up to 8 pu first peak current for a terminal short circuit.

The major parameters of the machine are shown in table 7.

Parameters	value
Synchronous reactance (x_d)	0.5 pu
Transient reactance (x_d')	0.22 pu
Sub-transient reactance (x_d'')	0.11 pu
Armature short-current time constant (τ_{sc})	0.045 sec
D-axis transient short circuit time constant (τ_d')	7.31 hr
D-axis transient short circuit time constant (τ_d'')	0.01 sec
Armature resistance (r_a)	0.007 pu

Table 7. DSC electric parameters

Figure 24 compares the efficiency of the DSC with a conventional synchronous condenser. The HTS field winding eliminates 50% of conventional machine field losses. Especially, It has good efficiency in light load condition.

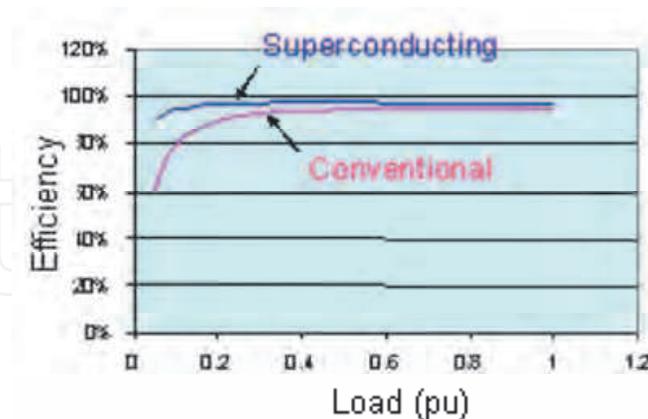


Fig. 24. DSC versus conventional machine efficiency

The DSC has no dynamic stability limit within its MVA rating. The machine can run stably without requiring any feedback control for dynamic voltage stabilization. This machine also has a superior dynamic stability during small oscillations and requires no field forcing for damping such oscillations. Figure 25 shows its damping of oscillations following a sudden change of load.

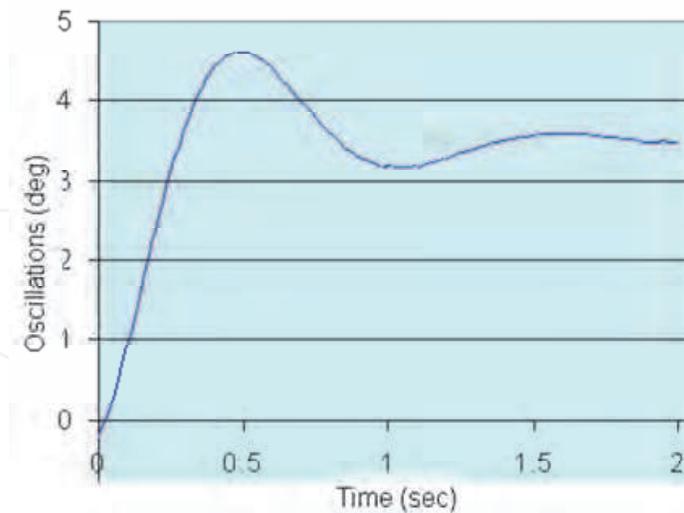


Fig. 25. DSC damping of low frequency oscillation following sudden load change

5. Application to power system

5.1 HTS cable

Before HTS cable application to power system, system planners have to understand the characteristics of power system and HTS cable. HTS cable system shall be applied special place in network which requires higher density power transmission.

There are several feasibility studies for HTS cable application. J. Jipping et al examined application validity of HTS cable for future load growth in a viewpoint for heat capacity and fault current. D. Politano et al examined technical economical efficiency for substitution high voltage transmission line for HTS cable. K. C. Seong et al examined transmission capability problem of power systems in a viewpoint for power flow and examined validity for HTS cable application. G.J.Lee et.al[] presented HTS cable application method to increase voltage stability limit. Recently, Ultera finished feasibility study of Amsterdam HTS project which will connect 6km, 50kV 250MVA HTS cable in 2013~2014 to increase inter-substation power transfer. Also, AMSC is planning to use DC HTS cable to interconnect North America network (Tres-Amigas Project).

For every application, total power system planning techniques are needed for the future's HTS cable implementation.

In this section, an example of HTS application study method shall be introduced to increase voltage stability limit. Fig 26 represents study procedure .

5.1.1 Case study

Sample system and verify initial transfer capacity

IEEE 39 bus system is considered for the sample system (Fig. 27). N-1 contingency is applied to estimate initial steady state transfer capacity. From the initial load condition (6098MW), maximum incremental transfer capacity applied N-1 contingency case is 3900MW. Therefore, system transfer capacity regarding security limit is 9,998MW.

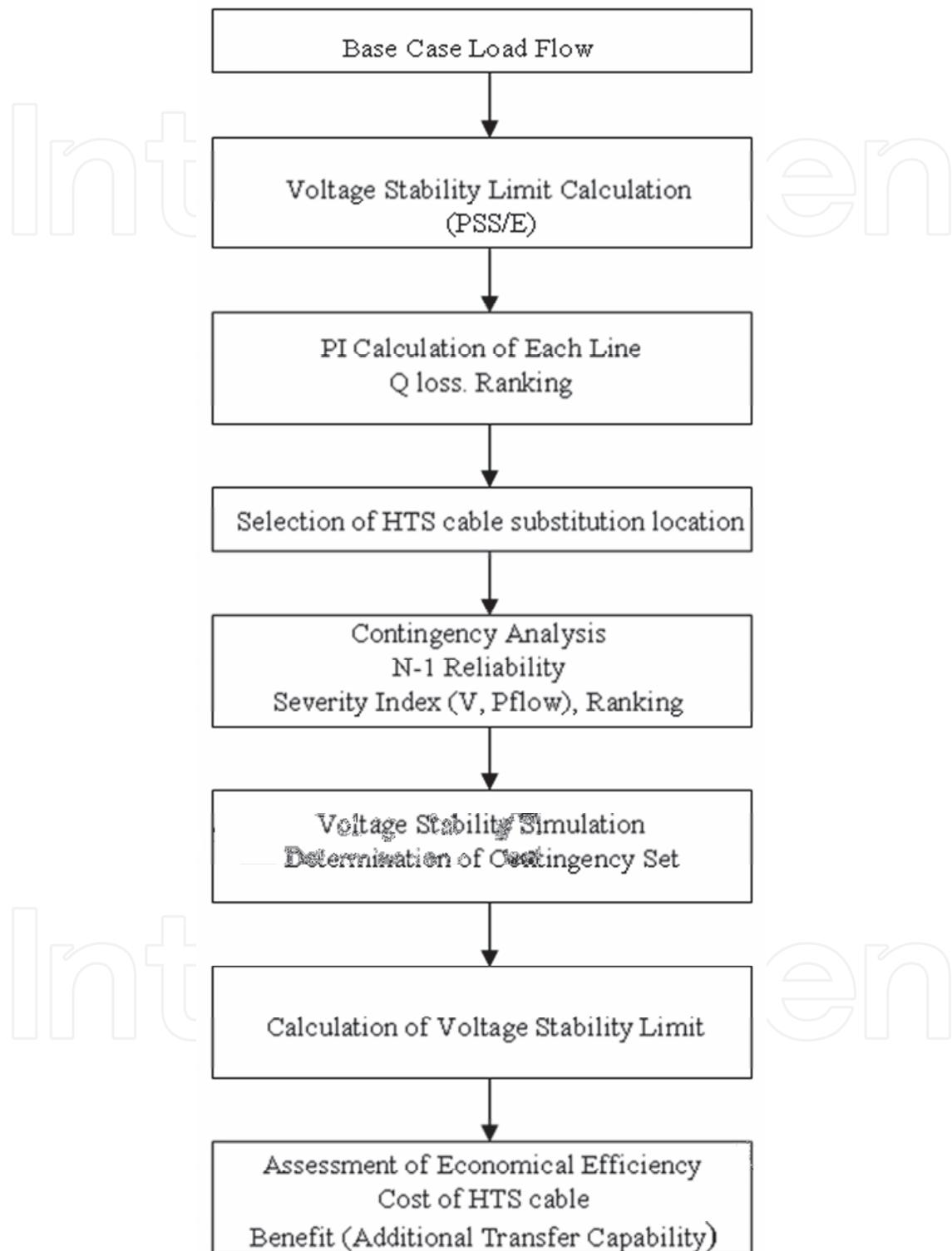


Fig. 26. Analysis procedure of HTS cable application

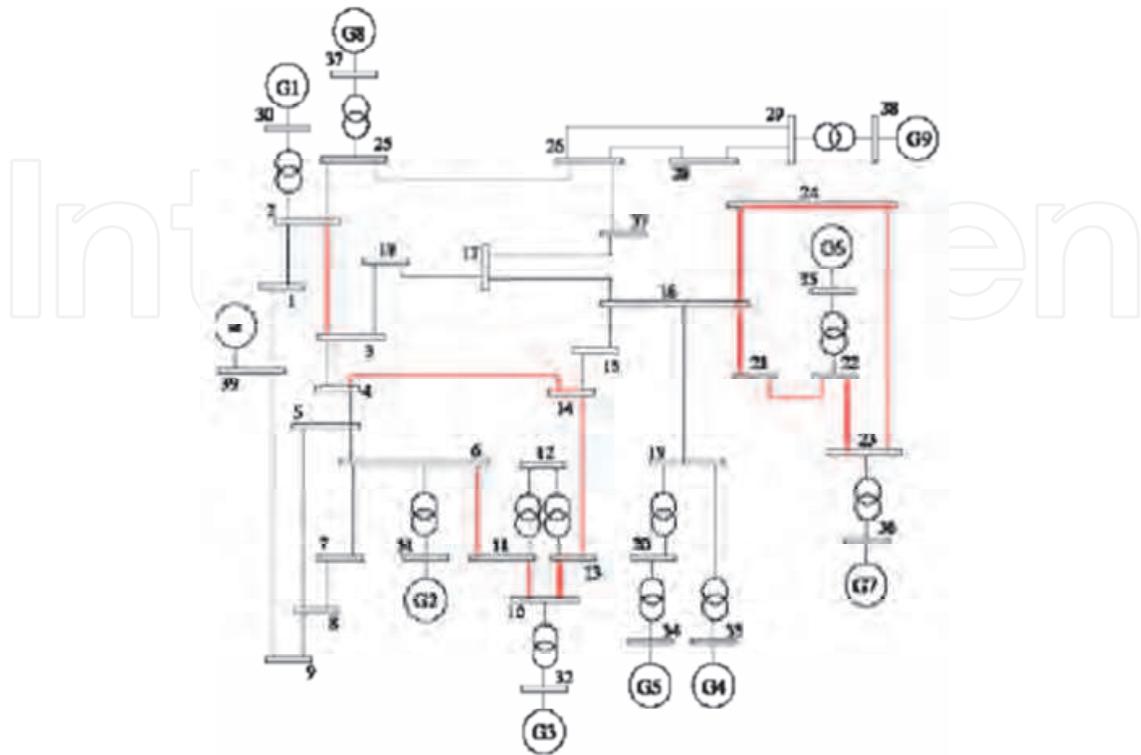


Fig. 27. IEEE 39 bus systems (HTS cable application: red line)

SI calculation of sample system

To consider power system reliability, N-1 contingency criteria was applied. Equation (3.1) and (3.2) shows the severity index (SI, over load index and voltage index) used in ranking.

① Over-load index

Equation 3.1 represents over-load index.

$$PI = \sum_{i=1}^L \left(\frac{P_i}{P_{\max,i}} \right)^2 \quad (10)$$

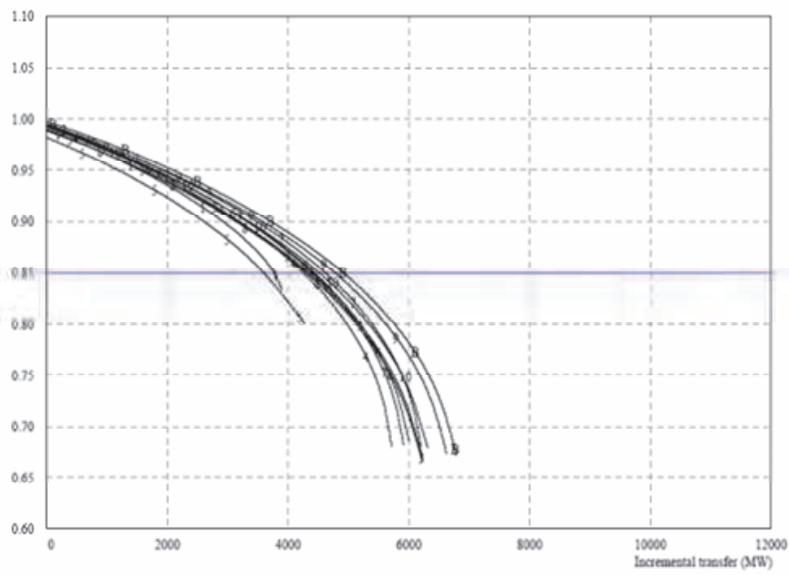
② Voltage index

Consumption of reactive power can be known by voltage ranker which represents increment of reactive power loss by increased load factor of line. Equation 3.2 represents voltage index.

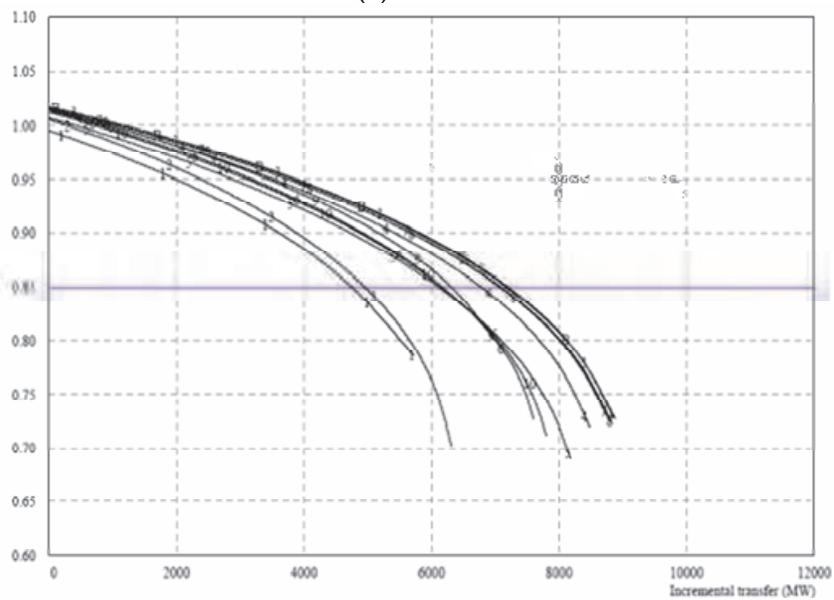
$$PI = \sum_{i=1}^L X_i P_i^2 \quad (11)$$

where P_i is active power, X_i reactance, and $P_{\max,i}$ power ratings of i -line.

The results of SI on sample system results are shown in Table 3.4 and Table 3.5. As a result of calculation, the first two contingency cases of each SI are determined as the object cases of voltage stability calculation.



(a) before



(b) after

Fig. 28. P-V curve (HTS cable application)

Ranking No.	Contingency Line		PI[p.u.]
	From Bus	To Bus	
1	21	22	10.8136-
2	23	24	8.6842
3	6	11	8.6463
4	13	14	8.6206
5	15	16	8.5228

Table 8. Performance index by line overload index

Ranking No.	Contingency Line		PI[p.u.]
	From Bus	To Bus	
1	28	29	10.8884
2	2	3	10.3888
3	16	21	10.2108
4	2	25	9.9931
5	6	7	9.8334

Table 9. Performance index by line voltage index of case I

Table 10 is the summary of the overloaded lines at severe contingency cases. HTS cable is applied as the order of severity of overloaded line. The replaced system is shown as Fig.29. Considered HTS cable constants are $L = 0.10[\mu\text{H}/\text{km}]$, $C=0.29[\mu\text{F}/\text{km}]$ respectively. Incremented transfer capacity after HTS cable replacement is 8,880MW in base case and 5720MW in N-1 contingency case. Therefore, increased transfer capacity becomes 1820MW.

from	to	contingency	rating	flow	overload(%)
16	24	OVRLOD 1	600.0	630.4	105.0
22	23	OVRLOD 1	600.0	665.5	107.9
23	24	OVRLOD 1	600.0	945.9	157.5
16	21	OVRLOD 2	600.0	681.0	111.3
21	22	OVRLOD 2	900.0	955.9	104.2
4	14	OVRLOD 3	500.0	566.2	113.7
10	13	OVRLOD 3	600.0	620.8	102.3
13	14	OVRLOD 3	600.0	636.3	105.5
6	11	OVRLOD 4	480.0	636.8	132.3
10	11	OVRLOD 4	600.0	618.2	102.1

Table 10. Overloaded lines at N-1 contingency

5.2 SFCL

In power system, proper SFCL application places are considered as (a)~(c) points of Fig. 29. Point (a) is to limit fault current of distribution feeder. SFCL at (b) point reduces fault

current impact of adjacent transformer in case of parallel operation and protects bus bar. Point (c) is general solution to reduce transformer secondary fault current and extend Circuit Breaker changing time when distribution system experiences high fault current.

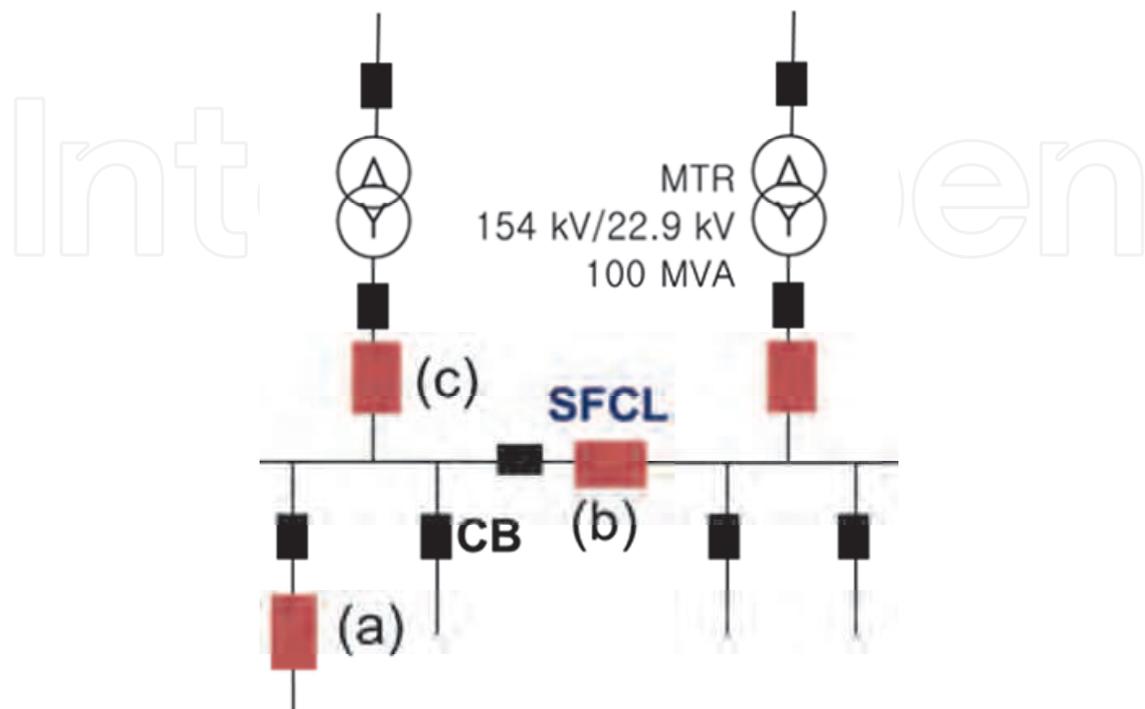


Fig. 29. SFCL application

6. Conclusion

The infrastructure of electric power system is based on conductor. With the change of power industry, such as Kyoto protocol and Energy crisis, superconducting technology is very promising one not only to increase efficiency of electricity but also to upgrade security of power system. Among various superconducting technology, most applicable ones -HTS cable, Fault current limiters, Dynamic SC are introduced and discussed how to apply.

Other superconducting facilities, like transformer, generator, SMES, Superconducting Flywheel, are in testing and will be implemented with the changes of power market needs.

However, the most critical obstacle of power system application is superconductor material and cooling system. Present HTS superconductors have to be improved much more than conventional ones, but still have difficulties in general use, such as extreme low temperature operation, hard manufacturing, AC loss and high cost. Cooling system is also hard task which have close relation of HTS failure due to quench mechanism. In operating point of view, monitoring and control to protect the local hot spot is another task to overcome.

More advanced superconductors and application methods are expected in power system usage in near future.

7. Acknowledgment

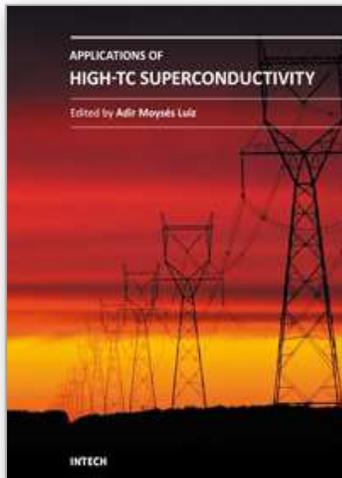
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This book is a collection of the chapters intended to study only practical applications of HTS materials. You will find here a great number of research on actual applications of HTS as well as possible future applications of HTS. Depending on the strength of the applied magnetic field, applications of HTS may be divided in two groups: large scale applications (large magnetic fields) and small scale applications (small magnetic fields). 12 chapters in the book are fascinating studies about large scale applications as well as small scale applications of HTS. Some chapters are presenting interesting research on the synthesis of special materials that may be useful in practical applications of HTS. There are also research about properties of high-Tc superconductors and experimental research about HTS materials with potential applications. The future of practical applications of HTS materials is very exciting. I hope that this book will be useful in the research of new radical solutions for practical applications of HTS materials and that it will encourage further experimental research of HTS materials with potential technological applications.

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