WESTERN POWER DISTRIBUTION
INNOVATION

NEXT GENERATION NETWORKS

SUPERCONDUCTING CABLES- NETWORK FEASIBILITY STUDY

WORK PACKAGE 1

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Contents

Glossary

Abbreviation	Term
AMSC	American Superconductor Corporation
CD	Cold Dielectric
DNO	Distribution Network Operator
EPR	Ethylene Propylene Rubber
HTS	High Temperature Superconductor
LN_2	Liquid Nitrogen
PPE	Personal Protective Equipment
VLF	Very Low Frequency
WD	Warm Dielectric
WPD	Western Power Distribution
XLPE	Cross-linked Polyethylene

Chapter 1

Introduction

1.1 The Motivation Behind This Feasibility Study

The increasing number of electricity distribution networks reaching their capacity limits means that the need for network reinforcement will continue to grow. Reinforcing the networks using conventional approaches includes building new electricity substations and installing additional transformers. This is incredibly challenging in urban environments due to limited land availability and high costs, hence creating the need to investigate alternative solutions.

This study examines the feasibility of using High Temperature Superconducting (HTS) cables in UK electricity distribution networks to address the problem.

Compared with conventional copper power cables, superconducting cables can offer a number of unique benefits:

- Under the same power transmission voltage level, the current carrying capability of HTS cables is three to five times more than that of conventional copper cables. This means that a superconducting cable could replace a number of conventional cables, requiring less space and land.
- Superconducting cables can carry equivalent power capacity at a much lower voltage level which could enable the replacement of large, expensive high voltage conventional cables with lower voltage superconducting cables.
- Superconducting cables can carry AC current with much lower losses compared to conventional cables.
- Due to its very high current density, superconducting cables could be of very compact size, providing a promising solution where underground space is limited.
- As superconducting cables have no thermal and electromagnetic impact on its surroundings, it is suitable to install them in the already existing underground pipelines, thus expanding the power transmission capacity.

These unique characteristics of High Temperature Superconducting cables make them an attractive technology, especially in urban areas where underground space and land availability is limited. In these urban areas, the networks are most often reaching their capacity limits, making the case for investigating the feasibility of using HTS cables in electricity distribution networks even stronger.

1.2 The Objective

This project is a feasibility study with the aim to improve knowledge of the technology's benefits, challenges and costs to determine whether a superconducting cable demonstration project is appropriate.

The project will assess the benefits and technical issues of using superconducting cables to provide additional capacity in dense urban environments. In such locations land prices or availability can be problematic in establishing new substations. As the first comprehensive study examining the feasibility of using superconducting cables in UK distribution networks, it will provide significant learning and could possibly lead to the UK's first trial.

1.3 The Three Work Packages

This feasibility study consists of the following 3 work packages:

Work Package 1

Work Package 1 forms a comprehensive Cost Benefit Analysis (CBA) of existing Superconducting cable technologies and detailed comparisons of all of their aspects to traditional solutions.

Work Package 2

In this work package, a site for the possible installation of a trial superconducting cable in WPD's network will be selected and a detailed study will be undertaken to justify the selection of the site, explaining the installation procedures and requirements and analysing the costs. The study will also consider the future requirements of the installation, which includes operational procedures, maintenance, response to faults, repair and modelling of installation in WPD's power system analysis tools. Finally, all of the aspects of the proposed implementation will be compared to the conventional solution to provide clear conclusions.

Work Package 3

Work Package 3 will provide an overview of the learning and knowledge that was captured in the previous two stages and will make appropriate recommendations for a network trial.

1.4 Introduction to Work Package 1

This report presents the findings of Work Package 1 of this network feasibility study.

To make the motivation behind this work clear to the reader, the document starts with an overview of the problem that we are trying to solve, highlighting the importance of finding new ways of adding capacity to our existing electricity distribution networks.

As the aim of the study is to assess the feasibility of using superconducting cables to provide additional capacity, Chapter 3 provides an overview of the history and development of superconducting cable technologies, including previous worldwide demonstration projects.

Then, in Chapter 4, the key aspects of Superconducting Cable implementations are investigated. This is providing sufficient knowledge to understand the structure of such systems and their main challenges.

In Chapter 5, the same aspects are explored for the conventional cables which are currently being used by most Distribution Network Operators.

The information presented in Chapters 4 and 5 is then used to compare each and every key aspect of superconducting and conventional cables. This forms the Cost Benefit Analysis of Chapter 6.

Finally, based on the CBA of Chapter 6, Chapter 7 presents the main conclusions and how these shape the direction the work will follow in Work Package 2 of this network feasibility study.

Chapter 2

The Problem

2.1 When Do We Need to Reinforce?

Electricity distribution networks need to be designed such that they meet certain standards of security of supply which are specified in Engineering Recommendation P2/6. These standards are based on the capability of a network to meet its group demand after First and Second Circuit outages. Table 1 shows the different requirements. If these requirements cannot be met, then network reinforcement is necessary to ensure compliance.

2.2 A More Detailed Look into P2/6

For example, if a substation has a maximum demand of 11MW and has two transformers providing the infeeds, in the case that one of the two infeeds is lost (First Circuit Outage or otherwise known as an n-1 case), 11MW needs to be restored within 3 hours. This is achieved by ensuring that the other transformer can provide that load, meaning that each transformer should have a rating of at least 11MW (substation's maximum demand).

Class of supply	Range of Group Demand	Minimum demand to be met after: First Circuit Outage	Minimum demand to be met after: Second Circuit Outage	Notes
A	Up to 1MW	In repair time: Group Demand	Nil	Where demand is supplied by a single 1000kVA transformer the "Range of Group Demand" may be extended to cover the overload capacity of that transformer.
B	Over 1MW and up to 12MW	(a) Within 3 hours: Group Demand minus 1MW (b) In repair time: Group Demand	Nil	
C	Over 12MW and up to 60MW	(a) Within 15 minutes: Smaller of (Group Demand minus 12MW); and 2/3 of Group Demand (b) Within 3 hours: Group Demand	Nil	Group Demand will be normally supplied by at least two normally closed Circuits or by one Circuit with supervisory or automatic switching of alternative Circuits.
D	Over 60MW and up to 300MW	(a) Immediately: Group Demand minus up to 20MW (automatically disconnected) (b) Within 3 hours: Group Demand	(c) Within 3 hours; For Group Demands greater than 100MW: Smaller of (Group Demand minus 100MW); and 1/3 Group Demand (d) Within time to restore arranged outage: Group Demand	A loss of supply not exceeding 60 sec is considered as an immediate restoration. The Recommendation is based on the assumption that the time for restoration of Group Demand after a Second Circuit Outage will be minimised by the scheduling and control of planned outages, and that consideration will be given to the use of rota load shedding to reduce the effect of prolonged outages on consumers.
E	Over 300MW and up to 1500MW	(a) Immediately: Group Demand	(b) Immediately: All consumers at 2/3 Group Demand (c) Within time to restore arranged outage: Group Demand	The provisions of Class E apply to infeeds to the distribution system but not to systems regarded as part of the interconnected Supergrid to which the provisions of Class F apply. For the system covered by Class E consideration can be given to the feasibility of providing for up to 60 MW to be lost for up to 60 seconds on First Circuit Outage if this leads to significant economies. This provision is not intended to restrict the period during which maintenance can be scheduled. The provision for a Second Circuit Outage assumes that normal maintenance can be undertaken when demand is below 67%. Where the period of maintenance may be restricted paragraph 3 of section 2 applies.
F	Over 1500 MW	In accordance with the relevant transmission company licence security standard		

Table 2.1: P2/6 Security of supply requirements

Let's consider a 132kV/11kV substation with two 132/11kV transformers, T1 and T2, each of 60 MVA (summer)/78 MVA (winter) rating.

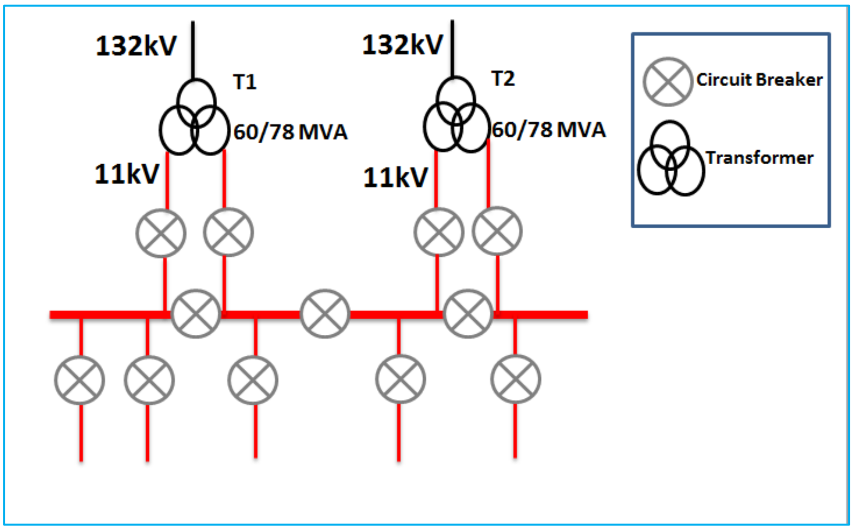


Figure 2.1 - Example 132/11kV substation

Such a substation would be designed for cases when the maximum demand fed by the substation would be expected to be less than 78 MVA. This is class of supply C and as shown in Table 1, to meet the security of supply standards, it must be possible to restore 52MW within 15 minutes under a First Circuit Outage (FCO). In the case that one of the two transformers failed or during a planned outage, the other one would be able to feed the entire substation load, meeting the P2/6 requirements.

As the load keeps growing over the years the substation could need modifications to satisfy the security of supply requirements.

Let's suppose for example, that due to load growth over the years, the group demand of the substation is expected to reach 100MVA. In that case, 100MW minus up to 20MW of automatically disconnected demand would need to be restored immediately in the case of First Circuit Outages. As the transformers are rated at 78MVA, they wouldn't be able to support the entire load in n-1 scenarios. This brings us to the following conclusion:

When the maximum demand of a substation with two transformers exceeds the lowest rating of the two transformers, P2/6 requirements are not satisfied under FCOs. Therefore, the substation would need to be reinforced.

To solve this problem, the following options exist:

1. Build a new 132/11 kV substation nearby to feed the additional load and part of the substation's existing load.
2. Replace the transformers with two transformers of higher rating.
3. Provide an 11kV interconnection between the substation and another 132/11 kV substation that has spare capacity.

4. Add a third transformer at the substation.
5. Install a third transformer at a site nearby and connect it to the substation at 11 kV.

Option 1 involves building a new substation to cater for the increasing demand. This requires purchasing land to build the substation which in certain occasions can be a challenge. In urban locations for example, land is not only very expensive but very often its availability is limited. Additionally, work would be required on the 11 kV side of the existing substation to shift some of its current load to the new substation.

Replacing the transformers is option 2, which also requires the replacement of the transformer circuit breakers, 11kV busbars or the replacement of the 132kV cables providing the infeed's (if the 132kV network is in ring configuration). This involves significant work and costs, but compared to option 1, in many cases it does not require the purchase of land. However, transformers of higher capacity are also larger in size, so this option is not feasible at sites where the space available is limited which is very often the case. Purchasing land to extend the substation could be a solution to this challenge but it is not always possible.

Option 3 involves the interconnection of the substation with a nearby substation operating at 11 kV. This option takes advantage of the spare capacity of the surrounding networks and could be a good alternative to options 1 and 2. The main constraint of this is that high capacity conventional cables operating at lower voltages cannot be used over long distances due to their high losses and large voltage drop. 11kV cables for example are typically used for distances only up to 2kms in urban locations.

Alternatively, a third transformer could be installed at the substation. This would require space on site for the additional transformer, the provision of another 132kV infeed and modifications to the 11kV switchboard.

Option 5 combines a number of different characteristics of the other options. It avoids the purchase of land by installing the third transformer at a nearby substation where there is space and capacity available. An interconnection at 11kV is also necessary, making it unfeasible if the distance between the two sites is large.

The different reinforcement options are summarised in Table 2.2.

	Option 1	Option 2	Option 3	Option 4	Option 5
Requires purchase of land.	■				
Requires additional space on site.		■		■	
Requires additional space at a different site.					■
Requires interconnection between substations.			■	■	■
Requires purchase of one transformer.				■	■
Requires purchase of more than one transformer.	■	■			
Requires additional 132kV infeed or 132kV modifications.	■	■		■	
Could require 11kV switchboard modifications.		■	■	■	■

Table 2.2 - Summary of traditional reinforcement options

2.3 Conclusions

As can be seen from Table 2, each traditional reinforcement option has its own benefits and drawbacks. Building a new substation is the most expensive solution and is not always an option at locations where land availability is limited. Options 2, 4 and 5 all require the purchase of at least one additional transformer which not only is expensive but could also require the purchase of additional space and in certain cases this is not possible. From all the options, Option 3 seems to have the least constraints. Interconnecting the substation with the growing demand to another nearby substation that has spare capacity, enables us to make the most efficient use of our existing networks and eliminates the need for buying land or additional transformers. This option, however, cannot be implemented with conventional cables at distances larger than 2 km in urban locations, due to their high losses and significant voltage drop.

Being able to perform interconnections between substations to transfer bulk amounts of power over any distance could provide a solution to the problem.

The following benefits would be offered:

- It would not be necessary to build new substations to support large increases in load.
- It doesn't require the replacement of the existing transformers with high capacity ones, which often requires additional space, not always available.

- Transferring capacity between existing substations would not be restricted by the characteristics of conventional cables, providing an alternative solution to any situation and not just when the distances are short.
- It would provide more flexibility in the usage of the network and enable DNO's to make the most of their existing assets.
- It could be the only solution in urban locations where land is expensive and not readily available.

This is exactly what superconducting cables can potentially enable us to do. Due to their low losses and high current density, they can be used to transfer large amounts of power, providing a way to interconnect substations and enhance the network capacity where it is needed.

Chapter 3

History and Development of Superconducting Cable Technologies

3.1 Introduction to Chapter 3

The objective of this chapter is to provide an overview of the history and development of superconducting cable technologies. This chapter starts with the background of the superconductivity technology, with particular focus on the superconducting materials used in the manufacturing of superconducting cables. Then, the different types of superconducting cables are explained. The discussion then moves to the theoretical benefits and limitations of superconducting cables. Finally, to provide an overview of the development in this area until now, several previous worldwide superconducting cable demonstration projects are presented.

3.2 Development of Superconductivity and High Temperature Superconducting (HTS) Cables

3.2.1 History of Superconductivity

In 1911, the superconductivity phenomenon was first discovered in mercury by Dr. Kamerlingh Onnes. Mercury, when cooled down to 4K using liquid helium, suddenly a huge drop in its resistance is observed, with a net resistance of 0 Ω, thus making it a superconductor. Next to mercury, this superconductivity phenomenon is discovered in several other metals with varying temperatures (<20 K), which is technically termed as critical temperature (Tc). Figure 3.1 shows variation in the resistivity of the superconductor when compared to normal metal. When the temperature of the superconductor is lower than the critical temperature, its resistivity goes to zero. In other words, these materials can be operated as superconductors only when cooled down to the critical temperature or below critical temperature.

Therefore, superconducting cables need to be operated at temperatures below its critical temperature, which can be termed as nominal operational temperature. Since the critical temperature of early discovered superconductors is very low (less than 20 K), which results in the extremely high cost of cooling, it was not feasible to produce large scale superconducting power cables until the discovery of high temperature superconductors (HTS).

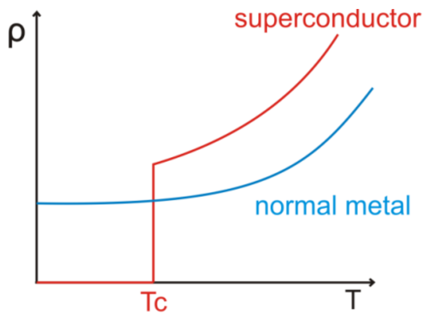


Figure 3.1: Critical temperature (Tc) of superconductor compared to normal metal

The discovery of HTS superconductors begun in 1987, with the Y-Ba-Cu-O (YBCO) composite showing the superconducting phenomena at a critical temperature of 92 K, exceeding the temperature of liquid nitrogen (77K). Then, in 1988, a critical temperature of 110K was achieved in the Bi-Sr-Ca-Cu-O (BSCCO) superconductor. Both of these HTS superconductors act as insulators at room temperature, making the physics behind these phenomena very interesting to the physicists. Surprisingly, in 2000, MgB2 which acts as metal at room temperature is discovered to have a critical temperature of 40 K, the highest in the intermetallic compounds, breaking the theories of superconductivity that existed until then. Table 3.1 summarizes the properties of the commercially available high temperature superconductors [1-3].

Thanks to their high critical temperature (Tc) values, these three types of superconducting materials (MgB2, YBCO and BSCCO) are widely being used for superconducting power application developments, such as superconducting fault current limiters, superconducting machines and superconducting power cables. YBCO or BSCCO, if used for superconducting cables, the critical temperature of the cables will exceed the liquid nitrogen temperature (i.e. 77 K). Meaning, the superconducting cable can be cooled down by just using liquid nitrogen, reducing the cooling cost of superconducting cables to far extent. Liquid nitrogen is currently being used as a very common industry coolant with a price tag of nearly 20 p per litre.

Material		BSCCO	YBCO	MgB_2
Availability	Form	Tapes, wires	Thin films	Tapes, wires
	Length	1-2 km	1 km	Nearly 3 km
J_C (A/cm^2)		5×10^5	1×10^7	1×10^6
J_{eng} (A/cm^2)		$21\text{-}25\times10^3$ (SEI)	14×10^3 (AMSC)	45×10^3 (Columbus) 2×10^5 (Hyper Tech)
T_C (K)		110	80 - 93	39
Working temperature		77	77	20-30
Optimum Cooling Medium		Liquid Nitrogen (LN_2)	Liquid Nitrogen (LN_2)	Gaseous He, Liquid H_2 Liquid Ne

Table 3.1: Properties of commercially available high temperature superconductors

3.3 Theoretical Benefits and Limitations

The advancement in superconducting cable technologies over the years has been significant, leading to the development of HTS cables with unique characteristics that are incredibly important for applications in electricity distribution networks. These characteristics and benefits over conventional cables are described in this section.

3.3.1 High Power Capacity with Compact Configuration

Under the same power transmission voltage level, the current carrying capability of the superconducting cable is three to five times [8] higher than that of a conventional copper cable, while the total losses of the superconducting cable including the cooling losses are only one-third of conventional copper [9]. Therefore, the efficiency of the power grid could be improved significantly using HTS cables.

At the same power transmission capacity, the size and the weight of superconducting cable reduce significantly when compared to conventional copper cable. Thus huge amount of power with very less losses can be transferred by compact superconducting cable requiring less space and minimum land.

3.3.2 Bulk Power Transfer at Lower Voltage Levels

Due to its very low impedance, superconducting cable dissipates very little resistive losses compared with the conventional copper cable. Hence, it is no longer required to operate the cable at very high voltages, to reduce the I2R losses. Thus, high voltage conventional cable can be replaced by low voltage superconducting cables for the same power rating.

Figure 3.2 gives the comparison between conventional XLPE cable and superconducting cable with power transmission capacity at rated voltage level. It can be seen that if the 230 kV voltage level is required for XLPE cable to transmit 500 MVA power, equivalently, only 69 kV voltage level is required for superconducting cable to transmit the same amount of power.

Replacing high voltage conventional cables with low voltage superconducting cables will result in fewer substations and switchgear, as shown in Figure 3.3. Ideally, the electrical power can be even directly transmitted from power plants to the distribution networks without any substations. Hence, significant investment saving could be possible if a superconducting cable implementation is considered.

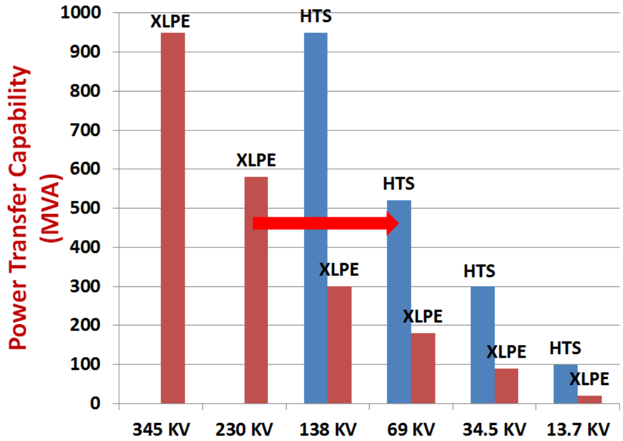


Figure 3.2: The power transmission capacity and voltage level of XLPE cable and superconducting cable. [10]

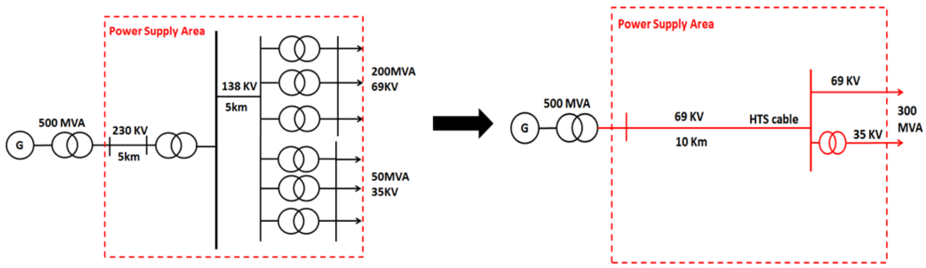


Figure 3.3: The simplified power network replaced by superconducting cable.

3.3.3 Limited Underground Space Requirements

Superconducting cables can be installed in the same underground electrical cable conduits as conventional cables, and provide additional capacity using existing underground space. Underground space in urban locations is limited and valuable, so superconducting cables could enable better usage of the available space, carrying, more than five times the power transmission capacity that can be achieved with the existing conventional cables.

Furthermore, superconducting cables have no outer magnetic field around the cable. The electromagnetic impact on other parallel cables is eliminated by using the superconducting screen. Additionally, there is no thermal impact on the environment, thus reducing the cable clearance requirements significantly.

3.3.4 Potential Cost Implications

Currently, the cost of copper is around 6-22 \$/kA·m, while that of superconducting tape is typically around 300-400 \$/kA·m. Therefore, it is clear that superconducting cables have very high capital costs. However, depending on the particular implementation, s superconducting cable system could offer cost savings in a number of areas [11]:

- Savings in the right-of-way cost.

The superconducting cable has a smaller cross-section with much larger current density and adding to this, there is no thermal and electromagnetic impact on surrounding area. Hence, it can transmit a large amount of power in small right-of-way. To transmit the same amount of power by conventional cables, multiple cables have to be used, which requires large right-of-way. In the urban areas, the cost of right-of-way could be extremely expensive and by using superconducting cable, the overall cost of the cable installation will be reduced to a large extent.

- Saving in the high voltage equipment costs.

Due to the negligible losses dissipated by superconducting cables, it becomes feasible to transmit electrical power at low voltage (11 kV and 33 kV). Hence, significant cost reduction can be achieved by avoiding all the expensive high voltage transformers (such as 132 kV/11 kV), switchgear and substations.

3.3.5 Impact of Superconducting Cables in System Power Flows

The unique characteristics of superconducting cables make them attractive for power system applications. However, their integration into the system could be challenging and there are several factors that need to be considered. One is the impact they can have on the system power flows when operated in parallel with conventional cables, as shown in Figure 3.4. Large share of power will be immediately diverted into the superconducting cable due to its low impedance, which can cause grid instability without any form of power flow control. [12]

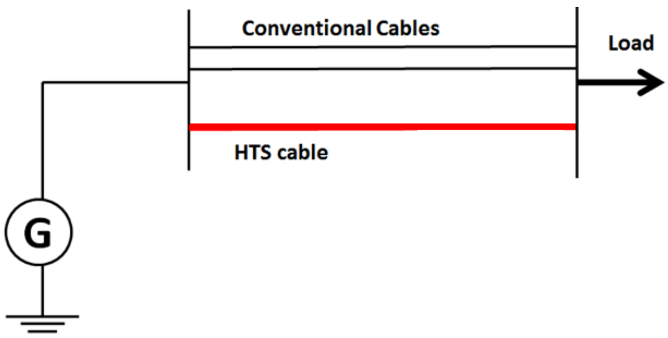


Figure 3.4: Conventional cables and superconducting cables working in parallel

3.4 Previous Installations

Although the superconductivity phenomenon was discovered late back in 1911, it was not actively used in large-scale power applications until 1987. This is because low-temperature superconductors require extremely high capital investment, especially for power transmission cables. It is the discovery of high temperature superconducting materials that triggered the development of superconducting electrical power cables, mainly due to its ability to operate at liquid nitrogen temperature, which requires relatively simplified cooling methods. In the past decade, several superconducting cable projects were demonstrated and implemented successfully around the world, which will be discussed in the following section.

3.4.1 Superconducting Cable Project in Japan (66 kV/1 kA/30 m)

A number of prototype superconducting power cable projects have been carried out in Japan, by Sumitomo Electric Industries, Ltd, since the discovery of HTS materials. The main aim of these projects was to demonstrate the huge current carrying capacity of superconducting cables.

In 1993, a superconducting cable of 7 m length with a critical current rating of 1000 A was demonstrated. BSCCO superconducting tapes were used for the cable construction, since they were the first commercially available superconducting material.

From 1997 to 1999, Sumitomo Electric demonstrated a 30 m long 66kV/1kA superconducting power cable, which being the world's first 66 kV voltage level superconducting cable. This project helped in making a considerable progress on the issues of long superconducting cable manufacturing process, large current capacity, and reliable dielectric in the liquid nitrogen environment. [13]

3.4.2 Superconducting Cable Project in China (35 kV/2 kA/33 m)

In China, Innopower Superconductor Cable Co., Ltd developed a superconducting cable with a warm dielectric design in 2004. This 33 m flange to flange cable is operated in the power grid with a rated operating current of 2 kA. This 3-phase 35kV cable system contained three single-phase superconducting cables with six superconducting cable layers each, making a total of 112 BSCCO superconducting tapes used for each cable. As the design implemented being warm dielectric, XLPE is used as the cable insulation material. Until 2012, it has been the only superconducting cable in the world with the longest operational time and transmitting the most electrical power in the real grid [14].

3.4.3 Superconducting Cable Project in the US (34.5 kV/0.8 kA/350 m)

The 34.5 kV/350 m/ 0.8 kA superconducting power cable project in Albany, NewYork was the first superconducting cable to be fabricated using YBCO tapes, supplied by SuperPower. The major accomplishments of this project include: usage of less superconducting tapes and the high current density. High current density with less tapes was made possible mainly due to the compact size of YBCO superconductor. This resulted in a considerable reduction in cable capital investment, thanks to the minimised usage of superconducting materials. [15]

3.4.4 Superconducting Cable Project in Germany (10 kV/2 kA/1000 m)

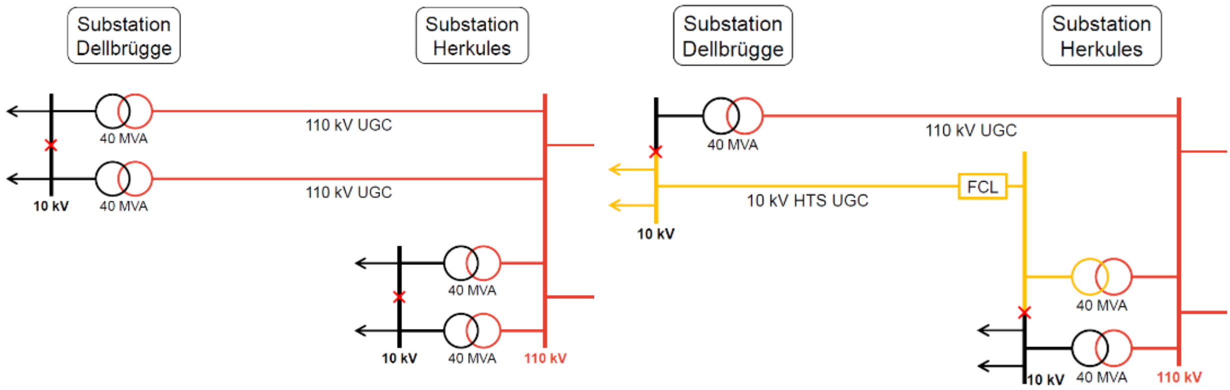
In 2014, the longest high temperature superconducting cable in the world was successfully installed into the electrical power grid in Germany. The aim of this project was to provide additional capacity to a substation with increasing demand by interconnecting it to a nearby substation which had a spare capacity.

At the early stages of this project, a similar feasibility study had been carried out which concluded that using superconducting cables in city centres for bulk power transfer offers a number of technical and economic advantages compared to conventional high voltage cables. Based on this study, a 1 km long 10 kV superconducting cable connecting the two substations was installed in the city of Essen, a pilot project supported by REW, Nexans and KIT, referred as 'AmpaCity'.

As shown in Figure 3.5, there are two alternative methods which can be used to expand the power demand in downtown substation Dellbrugge. Figure 3.5 (a) depicts the conventional cable solution, where the 110 kV conventional cables transmit the electrical power from the remote power grid to the Dellbrugge substation to meet the power expansion demand. A new 110 kV/ 10 kV transformer needs to be installed in the downtown area, so as to serve the increase in the power capacity of the existing Dellbrugge substation.

Alternatively, as in Figure 3.5 (b), a superconducting cable solution is applied. The 10 kV superconducting cable transmits the electrical power from the downtown area of Herkules substation (where spare power is available) to the downtown area of Dellbrugge substation, to meet the power expansion requirements. This avoids a need to install a new transformer as the existing one cannot take-in an additional power transformer.

Hence, as a result of installing AmpaCity superconducting cable, the 110/10 kV transformer was completely avoided in the downtown area of Essen by directly using 10 kV superconducting cable system. In comparison with the conventional 110 kV cable system, 10 kV superconducting cable has much simpler structure and requires much less underground space for cable ducts and auxiliary equipment installation. The overall investment of 10 kV superconducting cable system is said to be much lower than the additional conventional 110 kV power cable solution. [7]



(a) (b)

Figure 3.5: AmpaCity grid configuration (a) installation of conventional cable solution, (b) alternative installation of superconducting cable solution [16]

The design of the AmpaCity superconducting cable is based on the three-phase concentric structure. This cable uses a hollow former made of the corrugated metallic tube, which is used as the cooling channel for the liquid nitrogen. All the three phases are concentrically wound around the cable core and are separated by PPLP insulation layers. The resultant cable core is placed into the cryostat with a thermally insulated vacuum space.

Apart from the projects mentioned above, there are several other HTS superconducting cable projects implemented successfully around the world, as summarised in Table 3.2 [17-20].

Company	Rating	Length	Material	Location	Year
Sumitomo	22.9 kV/1.25 kA	100 m	Bi2223	Gochang	2006
Innopower	35 kV/2 kA	33 m	Bi2223	Yunnan	2004
VNIIKP	20 kV/1.4 kA	200 m	Bi2223	Moscow	2010
Sumitomo	34.5 kV/800 A	350 m	Bi2223	Albany	2006
Nexans	10 kV/400 MVA	1000 m	Bi2223	Essen	2013
Nexans	10 kV/1 kA	30 m	YBCO	Madrid	2008
LS cable	22.9 kV/ 50 MVA	400 m	YBCO	Seoul	2011
Nexans	138 kV/ 1.8 kA	30 m	YBCO	Hannover	2007

Table 3.2: List of HTS superconducting cable projects carried out around the world.

Chapter 4

HTS Superconducting Cables

4.1 Introduction to Chapter 4

This chapter investigates the main aspects of superconducting cable installations with the aim to improve the knowledge of their operation and limitations.

The key areas explored are:

- Mechanical construction and physical description.
- System components and requirements.
- Installation procedures and requirements.
- Operational procedures and requirements.
- Repair procedures and requirements.
- Lifetime assessment.
- Health and Safety considerations.
- Capital and operational costs.

The information presented in this Chapter will then form the basis of the Cost Benefit Analysis performed in Chapter 6.

4.2 Mechanical Construction and Physical Description

4.2.1 Physical Construction of Superconducting Cables

An HTS superconducting cable consists of one or more layers of superconducting tape-shaped wires, helically wound around a flexible central former, which could be a hollow tube or bundle of copper wires based on stability requirement. This central assembly of superconducting cable tapes, called a superconducting layer carries the electrical power. The superconducting cable layers are surrounded by a dielectric layer which is basically PPLP insulating tapes wrapped around the superconducting layers. PPLP is a very good dielectric, capable of operating at cryogenic temperature. Adding to this, it has a key advantage of being a good thermal conductor, hence aids in removing the heat from the superconducting layers very quickly. This dielectric layer is followed by either one or multiple superconducting cable layers acting as screening layers or other phases, space for liquid nitrogen flow, a surrounding cylindrical vacuum cryostat with multilayer insulation, and an outer protective jacket, as shown in Figure 4.1.

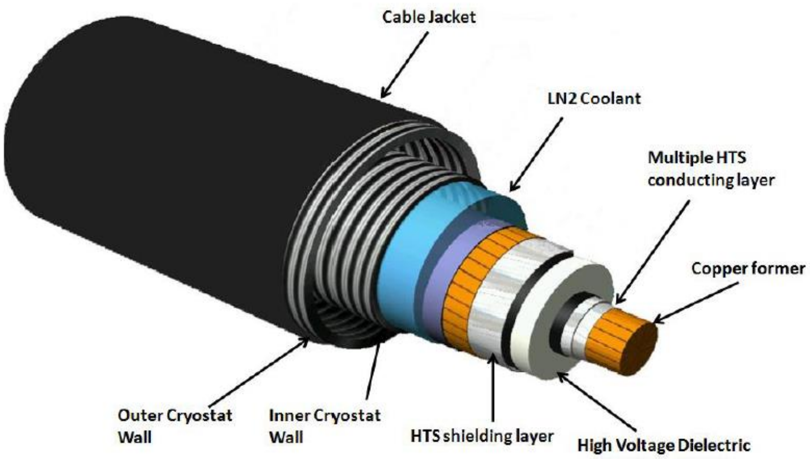


Figure 4.1: Single-phase superconducting cable. [4]

The functions of each layer of aforementioned superconducting cables are summarised in the table below:

Layer	Functions
Copper Former	The frame of the cable and conducting a certain amount of overload current when the superconducting cable is in faulty condition to prevent superconducting cable tapes from permanent damage.
Superconducting Cable Conducting Layers	The main current conducting layer, multiple conducting layers can increase the current carrying capacity.
PPLP Cold Dielectric Layer	The insulation layer that can withstand high transmission voltage in the cryogenic environment.
Superconducting Cable Shielding Layer	The shielding layer that prevents the leakage of the electromagnetic field.
Cryogenic Coolant	Constantly provides liquid nitrogen coolant to refrigerate the superconducting cable in order to operate below the critical temperature.
Inner and Outer Cryostat walls	The vacuum room between the inner and outer cryostat can provide thermal insulation to prevent thermal leakage.

Table 4.1: The functions of each layer in superconducting cables

The cryostat that encloses the HTS layers inside the cable, provides a cryogenic environment, to maintain superconductivity. Liquid nitrogen (65-77 K) is used as a cryogen and is made to circulate inside the cryostat. The cryostat is made so as to withstand the pressure developed due to liquid nitrogen circulation and also liquid nitrogen vaporization.

Superconducting cables use selective materials with very small thermal coefficients, but still due to the huge temperature difference between the room temperature and cryogenic environment, it makes it more vulnerable to thermal expansion/contractions. The thermal expansion for any length of conventional cable is about 0.1 % between room temperature and maximum operational temperature (90o). On the contrary, the thermal contraction for any length of the superconducting cable is about 0.3 % between the room temperature and operational cryogenic temperature (77 K). For superconducting cables (>1 km), it is necessary to carefully analyse and control its thermal contraction. Otherwise, a large contraction force will develop and cause irreparable damage to the superconducting cable and termination.

4.2.2 Superconducting Cable Categories

The superconducting cables can be broadly classified into two categories based on the positioning of insulation layer in the cable. They are: warm dielectric (WD) and cold dielectric (CD). During normal operation, if the insulation of the cable is at the room temperature, it is called warm dielectric and if it is at cryogenic temperature, it is called cold dielectric (CD) superconducting cable. The major difference is that, conventional cross-linkable polyethylene compounds (XPLE) insulation material widely used in the conventional copper underground cable can still be used in the warm dielectric superconducting cable. However, in the cryogenic environment, a material known as Polypropylene Laminated Paper (PPLP) should be used as the insulation for CD superconducting cable due to its special properties of flexibility (for bending the cable) and withstanding a high breakdown voltage in the liquid nitrogen environment.

Table 4.2 shows the comparison between the cold dielectric and warm dielectric design of superconducting cable. Since the cold dielectric design has many advantages, it is the most preferred cable design being adopted in the recent superconducting cable projects.

	Warm Dielectric	Cold Dielectric
Outer magnetic field	Yes	No
Losses	High	Low
Current capacity	High	Very High
Dielectric	XLPE	PPLP paper
Superconducting material consumption	Low	High (screen)
Cable inductance	Similar as conventional cable	Very low

Table 4.2: Comparison between warm and cold dielectric superconducting cable

4.2.3 Cable Configurations

Based on the superconducting layer layout for each phase and operating voltage, a variety of three-phase superconducting cable designs have been developed, which typically fall into three distinct categories:

- Three separate single-phase conductors in three separate cryostats, as shown in Figure 4.2. This kind of cable configuration is usually recommended for voltages typically over 132 kV.
- Three separate single-phase conductors in one single cryostat (Triad), as shown in Figure 4.3. This kind of cable configuration is recommended for voltages in the range of 33 kV or 66 kV.
- Three different phases wound in a concentric fashion over a single former, contained in a single cryostat (Tri-axial), as shown in Figure 4.4. This cable configuration is well recommended over its advantage of using less superconducting material over the other two designs for the same rated current. This design has been successfully implemented for cables rated up to 11 kV till date.

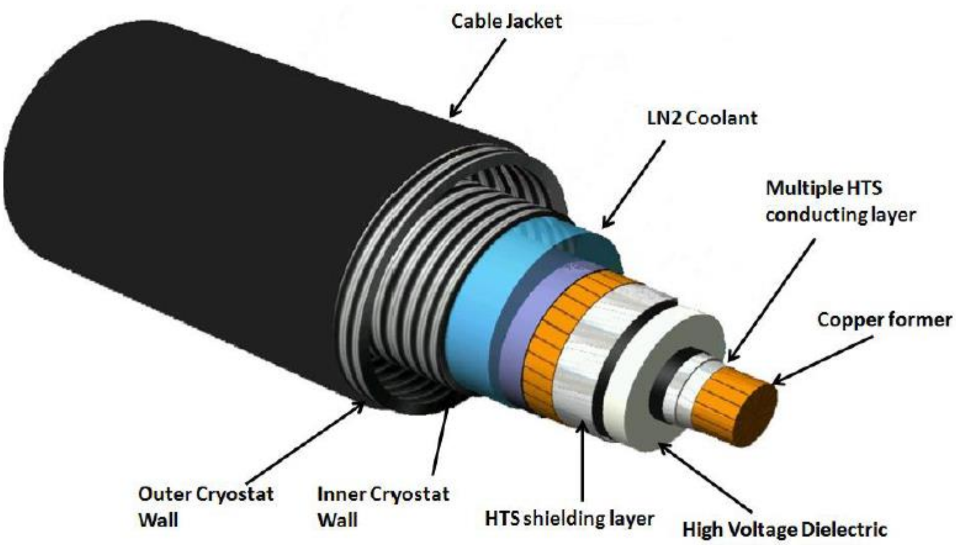


Figure 4.2 : Single-phase superconducting cable

Figure 4.3: Three-phase superconducting cable in one cryostat [4]

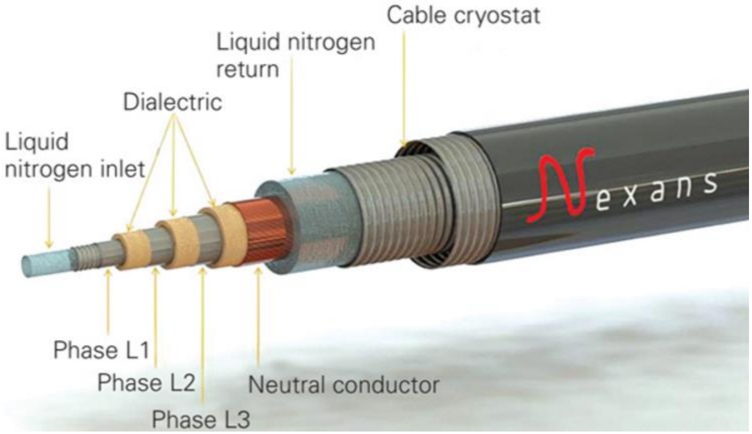


Figure 4.4: Configuration of the triaxial CD superconducting cable [4]

The triaxial superconducting cable has the most compact cable configuration, with each phase separated by a PPLP insulation layer, which is immersed in the circulating liquid nitrogen cooling path as well. The difference in applied current phase angle of each superconducting layer being 120°, the net electromagnetic field emanating from the cable will be zero, hence significantly reducing the stray field outside the cable. Unlike the superconducting shielding layer, required for the single core superconducting cable, only thin copper layer is used for shielding any unexpected stray fields. Thus, using tri-axial design, the usage of superconducting material is reduced by 50 %, thus saving a lot of capital cost.

The choice of particular configuration is mainly decided by the insulation thickness. In other words, the best cable configuration for each implementation depends on the cable voltage rating as shown in Table 4.3.

Voltage rating	Configuration
11 kV	Triaxial
33 kV	Triaxial or Three-in-one
132 kV	Three separated phases

Table 4.3: Recommended Superconducting cable configurations

4.3 System Components and Requirements

4.3.1 Cable Termination-Superconducting Cable to Power Grids

Superconducting cable terminations act as connectors between the conventional power grids at room temperature and a superconducting cable at cryogenic temperature. Superconducting tapes wound on the superconducting cable are connected with the cold end of the termination which is enclosed in the cryostat whilst the conventional copper cables from power grid are connected to the warm end of the termination, which is exposed to the room temperature.

Apart from the electrical connection, the termination also provides an interface point of the supply and return of the liquid nitrogen to the whole cable system so that the superconductors in the cable will stay in the superconductivity state. The design and manufacture of superconducting cable termination are vital to the long-term operational reliability of the whole superconducting cable system, and there are more complex requirements to superconducting cable terminations compared with conventional cable terminations. Besides all the functions performed by the conventional cable termination, the superconducting cable termination must have some unique functions, such as:

- Carry huge currents, in a range of a few thousand amperes while maintaining the cryogenic flow and electrically insulating the current leads.
- Thermally insulate the termination assembly from cold to warm region.
- Provide an interface for the liquid nitrogen flow stream.
- Compensates the thermal shrinkage of the cable during cool down time.
- Provides electrical field control across the interconnection.
- Manages the thermal gradient from cryogenic to ambient temperature.

There are different types of termination designs based on the superconducting cable configuration. For a single-phase superconducting cable configuration, a single-phase termination design is adopted, where each phase has its own termination enclosed in a cryostat. For triaxial superconducting cable configuration, a three-phase termination configuration is adopted where all three phases share a single cryostat. Figure 4.5 shows these two types of superconducting cable terminations. [4]

(a)

(b) (c)

Figure 4.5: Superconducting cable terminal configuration (a) three single-phase termination, (b) three-in-one termination, and (c) triaxial termination

4.3.2 Cable Joint-Superconducting Cable to Superconducting Cable

Superconducting cable joint is similar to a conventional joint, as it provides continuity for several cable components. A typical superconducting cable joint contains three main components: the conductor, the cryostat and the insulation. Copper is used as the conductor joint to provide the electrical continuity. In order to minimize the amount of heat generated from the copper conductor, a large cross-sectional area of copper should be used. The transition between the copper and superconductor tape requires the superconductor tape to be soldered on the copper joint. The cryostat joint is used to provide free flow of liquid nitrogen between two separated superconducting cables. There is a cryostat vacuum to minimize the heat leak through the joint as well. The dielectric insulation provides the insulation of the joint, which is similar to the conventional cable joint [4].

Figure 4.6: Superconducting cable to superconducting cable joint.

4.3.3 Cooling System

A superconducting cable cooling system contains a cooling station (can be a cryocooler or a liquid nitrogen storage tank), cable terminations and cryostat with liquid nitrogen feeding lines. The liquid nitrogen circulates in the cable loop to provide the cooling source. A circulation pump is installed in the liquid nitrogen circulating loop to ensure the liquid nitrogen flow rate and pressure. Heat dissipated from the superconducting layers results in the inlet and outlet temperature difference of the LN2, which is usually controlled within 5 K range by employing an additional heat exchange device [5].

To remove the heat by primary heat exchange, there are two techniques: one is using a bulk liquid nitrogen storage tank as the primary cooling source, which is the so-called open loop cooling system; and another using cryocoolers, called closed-loop cooling system. Regular refilling of liquid nitrogen in the storage tank is required for the open loop cooling system while continuous electrical power supply is required for the closed loop cooling system, after the initial cooldown of cable by liquid nitrogen. However, for superconducting cable of less than 2 km, the investment required for closed loop system would be a considerable amount, which compromises the economical operation for superconducting cable [6].

Hence, superconducting cables of less than 2 km could be implemented with an open loop cooling system so as to save an initial capital investment. However, for the superconducting cable with lengths of longer than 2 km, it is not feasible to implement liquid nitrogen storage tank due to the large quantities of LN2 storage required. Thus a closed loop cooling system is mostly used for superconducting cables of over 2 km length.

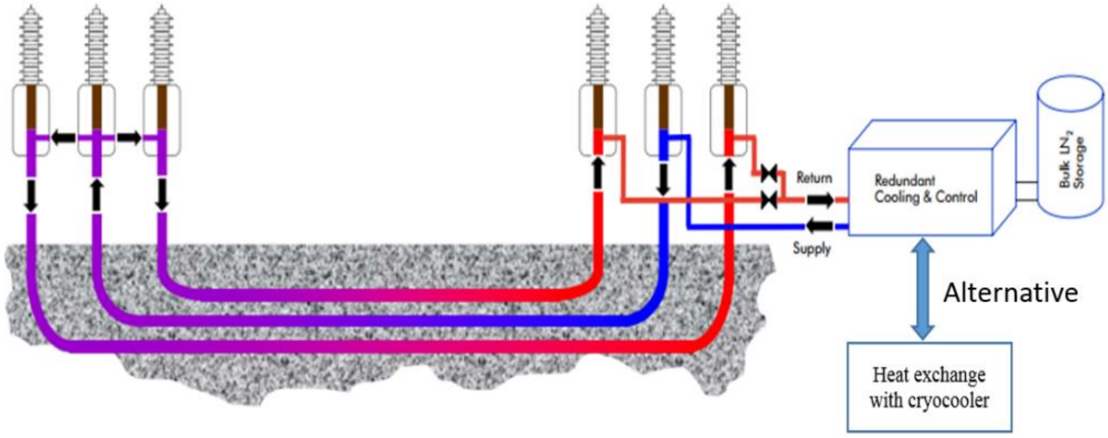


Figure 4.7: The self-circulating cooling system for superconducting cable. [7]

4.3.4 Components of Cryogenic Cooling System

As shown in Figure 4.8, the whole cryogenic cooling system for superconducting cable includes refrigerator, liquid nitrogen circulation pump, cryogenic heat exchanger and a liquid nitrogen storage tank. The above said components are the main parts of the cryogenic cooling system for a 1km superconducting cable, as recommended by the superconducting cable manufacturer [27].

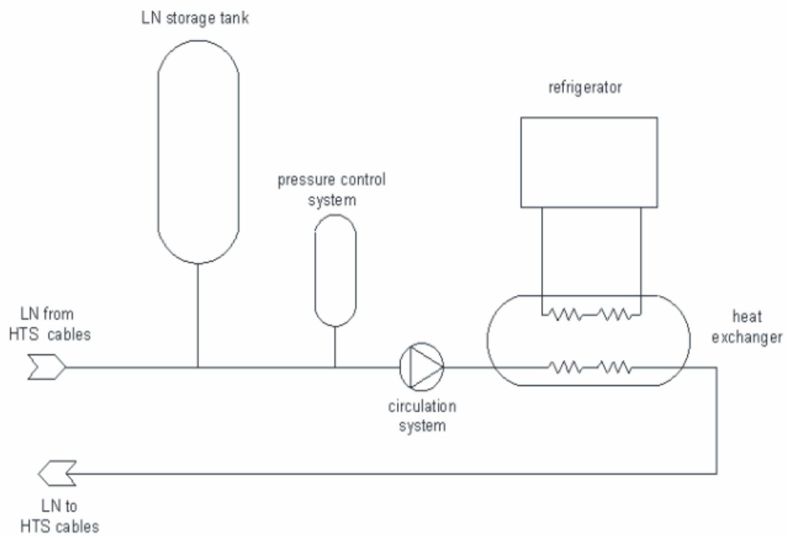


Figure 4.8: Structure of completed cryogenic cooling system.

4.3.4.1 Cryogenic Cooler (Refrigerator)

The main manufacturers of cryogenic coolers at liquid nitrogen temperature include Sumitomo Heavy Industries (Japan), Cryomech (US), Stirling Cryogenics (Netherlands) and Air Liquide (France), with cooling capacities ranging from a few tens to thousands of kilowatts. For a superconducting cable of 1km length, the total capacity required will be about 3 kW and hence 4 kW is recommended with redundancy. It is recommended that the superconducting trial project implements two sets of cryogenic coolers, one for operation and the other as backup. After considering the cooling capacity, reliability, price and maintenance cycle, it is recommended that the trial cable uses the Stirling cryogenic cooler SPC-4 as the main cooler and 6-8 units of G-M cryogenic cooler as back up. At 77 K, the unit output capacity of SPC-4 is 4 kW, and that of G-M is 700 watts. Both SPC-4 and G-M have maintenance cycles of more than 6000 hours.

4.3.4.2 Liquid Nitrogen Pump

Liquid nitrogen circulation for a kilometre-length superconducting cable requires a pressure head of not more than 0.5 Mpa. It is recommended that the trial project uses two sets of BNCP-64C-000 centrifugal liquid nitrogen pumps, one for operation and the other as backup. The pumps are to be installed in cryogenic dewar with appropriate thermal insulation. This particular model of liquid nitrogen pump is specially designed for circulating the sub-cooled liquid nitrogen and has a vacuum jacket for reduced heat loss. It has been successfully applied in superconducting cable demonstration projects initialised by Japan and Korea.

4.3.4.3 Cryogenic Heat Exchanger

This is for the heat exchange between the cryogenic cooler and the heated liquid nitrogen after circulation, and to ensure that the temperature of liquid nitrogen is at its set value before it circulates back into the superconducting cable. Components of the heat exchanger are manufactured using oxygen free copper and sealed in cryogenic Dewar with thermal insulation. The cryogenic Dewar is made of 304 stainless steel, which provides good heat insulation.

4.3.4.4 Liquid Nitrogen Storage Dewar

The storage tank serves as a reservoir of liquid nitrogen and uses high-vacuum power heat insulation, with an evaporation rate of less than 0.5% per day. It is recommended that the trial project uses a storage tank of 30 cubic metres, where liquid nitrogen is replenished every 6 months as the cable operates.

No.	Item	Proposed Parameters
1	Cooling method	Pressurised circulation of liquid nitrogen aided by cryogenic cooler
2	Cryogenic cooler	Stirling (main) and G-M (auxiliary)
3	Pressure head of liquid nitrogen pump	0.5 Mpa
4	Operating temperature	70-75K
5	Operating pressure	0.3-0.5 MPa
6	Coolant	Sub-cooled liquid nitrogen
7	Total cooling capacity	4kW
8	Total loss of cryogenic system	≤400W
9	Control method	Programmable remote control

Table 4.4: Recommended parameters of cryogenic cooling system

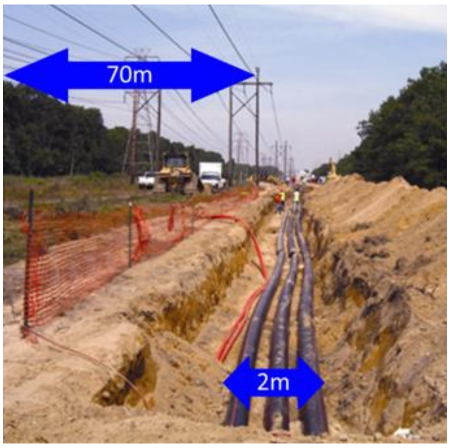
4.4 Installation Procedures and Requirements

The installation procedures of superconducting cables include: cable laying, connection of superconducting cables, connection of cables to terminals, connection of terminals to cryogenic system, and connection of control and monitoring systems. The steps involved in each of these procedures and the precautions to be taken care detailed below.

4.4.1 Types of Installation

Superconducting cables can be laid directly in the trench, or pulled into the ducts which are already available in the ground, run into the tunnels or laid above ground employing cable trays/ladders. The procedure employed is almost the same as the conventional cable installation.

For high voltages (≥ 66 kV), superconducting cables can be laid in a trefoil fashion (three cores arranged in a triangular formation), or flat, depending upon the requirements of the customer. For 11 kV and 33 kV, as the triaxial configuration is used, there is no need to consider the laying configuration.



(a) (b)

Figure 4.9: (a) Long Island 138 kV 575 MW HTS cable flat laying configuration (b) Three-in-one cable laying configuration [21]

For superconducting cables, there are no specific recommendations on laying configuration, due to the absence of its thermal and magnetic field impact on the surrounding environment. Figure 4.9 (a) shows the flat-layout configuration of 138 kV HTS cable in Long Island. However, if requested, the trefoil configuration could also be implemented as shown in Figure 4.9 (b).

4.4.2 Cable Transportation

HTS cables are carried by the specialised cable drums, whose inner diameter is limited by the minimum bending diameter of cables. The minimum bending diameter varies for different cryostat suppliers. Typically, the cable drum should be designed to have an outer diameter of 4.2 metres, inner diameter (cable bearing) of 3 metres, and width of 2.5 to 3 metres. A single unit of cable reels can carry only up to 500 - 700 metres of superconducting cables, which fulfils the requirements of over height transportation of regular highways. Figure 4.10 shows the appearance of HTS cable drum and transportation by trailer.

(a) (b)

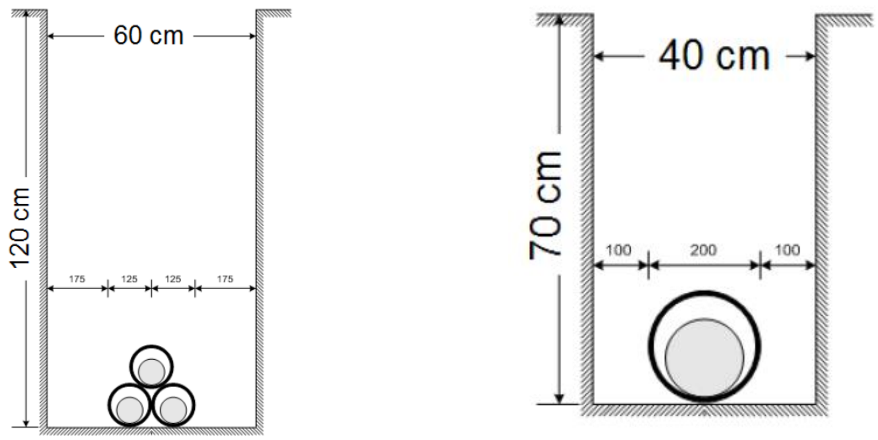
Figure 4.10: (a) Appearance of HTS cable drum. (b) Transportation of HTS cable [21]

Based on the transportation medium, the HTS cable can be carried by ship or trailer. Care should be taken, so as to avoid any damage to the cable core, caused by vibrations. Vibrations of large amplitude in the cryogenic corrugated pipe will result in causing significant damage to the HTS layers, as the diameters of the cable core and corrugated pipe are different. To test the influence of transportation vibration on HTS cable critical current degradation, significant tests have been carried out and the results reported showed no damage [22]. HTS cable has been subjected to continuous vibration of 3 hours, 3 g at 7 Hz, which is assumed to be the largest vibration during continuous transportation by trailer resulting in no damage or degradation. Similarly, the horizontal vibration caused by acceleration, also has no effect on the cable. The horizontal vibration caused during the ocean transportation is less than 0.2 g and that of land transportation is less than 1.0 g. Therefore, based on the transportation conditions in the UK, the superconducting cable can be safely transported in the same way as the conventional cable.

4.4.3 Trenches, Ducts, and Open Installation

Generally, the trench for superconducting cable has the same requirements as the conventional cable, reference made to ST: CA6A/3 (WPD's Standard Technique relating to the Installation of Underground Cables). However, for the same power rating, the dimensions of trench required by superconducting cable are much smaller than the conventional cable. Figure 4.11 shows the dimension requirements for 110 kV conventional cable and 10 kV triaxial HTS cable, with both cables having the same power rating. Trench dimensions for other superconducting cable ratings can be consulted with suppliers.

Ducts and pipes used for laying the HTS cable should be made as straight as possible. For conventional cables, there is a consideration of derating factor resulting from ducts, considering the thermal effects. However, there is no such de-rating effect for HTS cable, since the superconducting cable is thermally insulated from the outside cable environment.



(a) 110 kV conventional cable (b) 10 kV triaxial HTS cable

Figure 4.11: Dimensions of the trench for 110 kV conventional cable and 10 kV triaxial HTS cable [16]

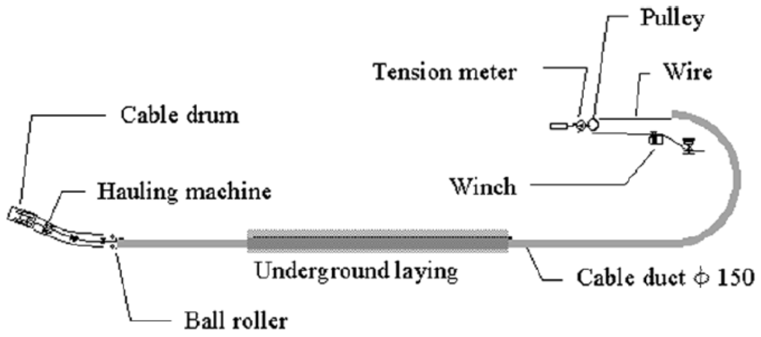
Open installation (for example, installing along a bridge where cable is completely exposed in the air) is feasible for superconducting cables and has very few restrictions when compared with conventional cable due to the absence of external magnetic field effects. Therefore, similar procedures and requirements for conventional cables can be referred to superconducting cables without much modification.

4.4.4 Cable Pulling

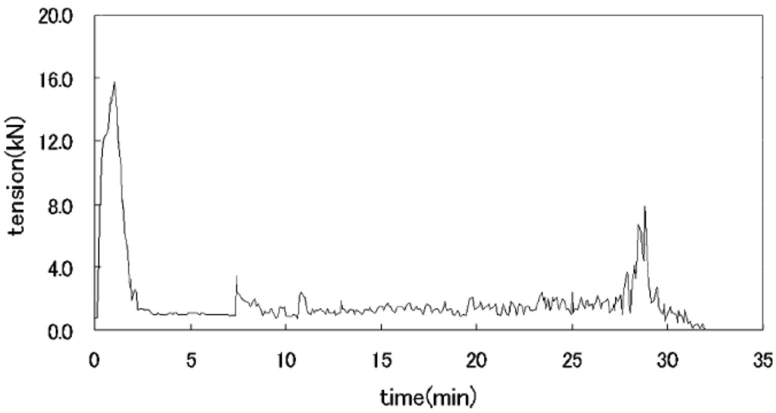
The superconducting cables can be installed into the cable ducts, already laid for the existing underground cables in the urban city areas or they can be directly buried in the trench when it comes to the rural area. The installation of superconducting cable involves pulling, a process similar to conventional power cables. Due to its light weight per unit length, pulling a superconducting cable in trenches or ducts with a mechanical winch is feasible.

The investigation on whether the HTS cable can be pulled directly into duct just like conventional cables was carried out in Japan, for a 500 m HTS cable installation [22]. Figure 4.12 (a) shows the schematic of HTS cable installation test. The 170 m installation route, contains 5 m bending radius section and underground section. Pulling-eyes were attached at the end of HTS cable. The cable was firstly pushed into the duct at the inlet by cable roller and was then pulled at the outlet of the cable duct by an electrical winch, very much similar to the conventional cable pulling process. During the cable pulling process, the pulling tension was measured by a tension meter at outlet of the duct. Figure 4.12 (b) shows the measured tension during installation. A maximum tension of nearly 16 kN was reached immediately after starting the pulling process, mainly due to the imbalanced speed between the winch and cable roller. The tension was then reduced to about 2 kN, when the speed of both became balanced. After 27 minutes, the tension again got increased to about 8 kN, which indicated that the cable was being pulled into the bending section.

In this installation test, it was verified that the superconducting tapes in the cable did not experience much tension, as most of the tension was mainly absorbed by the superconducting cable former. It was also verified that there was no damage to the HTS cable critical current properties and hence the HTS cable can be installed into the cable ducts or trenches, in the same way as the conventional cable.



(a)



(b)

Figure 4.12: (a) Schematic of the HTS cable installation (b) Pulling tension of the cable into the duct measured by a tension meter at the outlet of the duct [22]

The exact superconducting cable pulling force could be consulted with suppliers. For example, for AmpaCity project (10 kV/2 kA/1km), the cable cryostat was built so as to support pulling forces of at least 4,000 kg and a sidewall pressure of more than 10,000 kg.

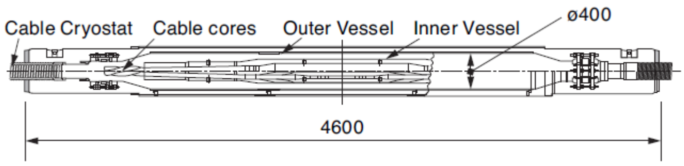
Figure 4.13: Pulling of HTS cable into the ducts [16]

4.4.5 Installation of Joints and Terminations

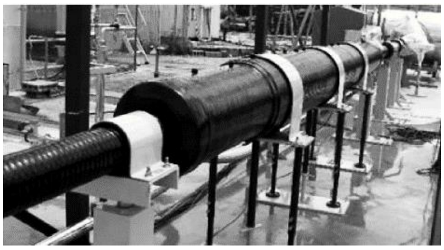
Depending on the transportation condition and bending limitations of superconducting cables, at least one joint is required, to install superconducting cables of length between 500 m and 1000 m. Terminations provided at both ends of the superconducting cable are required to make an interface between the electrical connections available at room temperature (conventional cables) and cryogenic temperature (HTS cable). The terminations should also take an additional responsibility of handling the liquid nitrogen circulation.

4.4.6 Installation of Joint

Development of joints involves the connection of all the functional layers of the first superconducting cable to the other using the prefabricated joints. Figure 4.14 shows an example of 3-in-one HTS cable joint design (Relevant to three-in-one cable configuration) [23]. A former is connected by using a copper sleeve and the HTS conductors are connected electrically by soldering. Dielectric insulation paper is wound around the superconducting layers, and the superconducting shielding layers are connected with solder as well. Braided copper wires are used to make press-in contacts for the copper shield layer, which is then finished by winding a protective layer around it. After interconnecting each of these three cable cores, liquid nitrogen tank and vacuum tank are assembled. The cable cores are not fixed onto the vessel so as to give enough room to accommodate thermal shrinkage of the cable.[24]



(a)



(b)

Figure 4.14: (a) Schematic view of "3-in-one" HTS joint. (b) Appearance of "3-in-one" HTS joint. [24]

Similar to the installation of joints in conventional cable, the superconducting cable should also be pulled with a sufficient overlap distance for creating joints. Figure 4.15 shows the 3 superconducting cable core joint processes.

(a)

(b)

(c)

Figure 4.15: Cable-to-cable joint assembly. (a) 3 cable core before connecting. (b) 3 cable core after connecting. (c) Joint box with vacuum cryostat. [25]

The joint bay for superconducting cable joint installation should be accessible to required equipment and personnel. For example, in AmpaCity project (10 kV/2 kA/ 1km), the joint bay had a width of 2 m, length of 6 m and a depth of 2.5 m, which was easily accessible during the installation and was backfilled after-wards. The position of the joint bay is normally arranged in the mid-distance of the total cable project.

However, since the configuration of superconducting cable joints is very complex and there are no standard installation procedures available to normal trained electrical technician to perform the joint installation, the superconducting cable joints installation process is recommended to be carried out by the cable manufacturers. In other words, the cable suppliers should be responsible to provide the on-site superconducting cable joint installation service.

4.4.7 Installation of Termination

The connection of superconducting cable to the terminals is to be completed at the demonstration site, including connection of electric conductors of superconducting cable to current leads of terminals, integration of cryogenic dewar tube and terminal cryogenic vessel, and construction of current leads for test and measurement. The current leads of superconducting cable have rigid structure and are connected to the electric conductors of superconducting cable through soft transition cable, which is bonded to the electric conductors by compression. The cryogenic dewar tube and terminal cryogenic vessel are integrated by dual vacuum layer plug, whereas the current leads for test and measurement are led out with a standard plug with cryogenic sealing function.

However, similar to the superconducting cable joint installation, since the configuration of superconducting cable termination is very complex and there are no standard installation procedures available to normal trained electrical technician to perform termination installation, the superconducting cable termination installation process is recommended to be carried out by the cable manufacturers. In other words, the cable suppliers should be responsible to provide the on-site superconducting cable termination installation service.

4.5 Operational Procedures and Requirements

This section will introduce the requirements of the cryogenic cooling system and preliminary operational procedures before energizing the cable system. It should be clearly noted, that the superconducting cable needs to fulfil the standards of factory/routine tests, according to Cigre TB 538 before energising.

4.5.1 Operational Requirements on Cryogenic System

A complete superconducting cable system comprises of a superconducting cable, cryogenic cooler, liquid nitrogen pump, cryogenic heat exchanger, liquid nitrogen storage tank and a cryostat pipe, as shown in Figure 4.16.

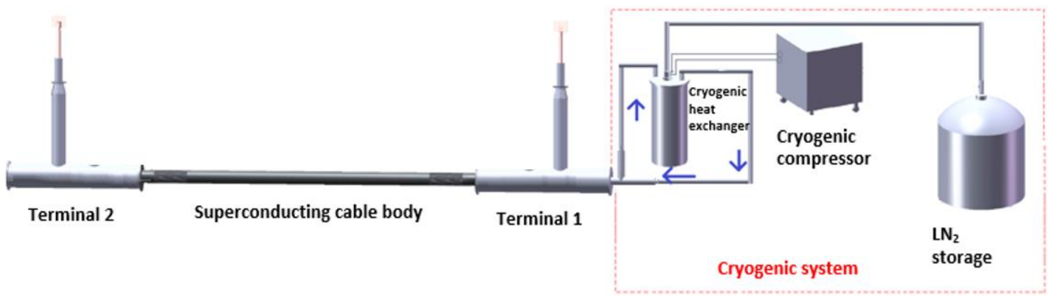


Figure 4.16: Schematic of superconducting cable cryogenic cooling system [32]

In order to maintain the superconductivity of the superconducting cable, the cable should be cooled down to cryogenic temperature, adopting pressurised circulation of liquid nitrogen, aided by cryocoolers. The circulation of liquid nitrogen during the cryogenic cooling process is detailed in a step wise manner as follows:

- liquid nitrogen is first injected into the superconducting cable through terminal 1 and will flow towards another terminal through the flexible interior of the electric conductor layer.
- Inside Terminal 2 the direction of liquid nitrogen flow reverses and gets back into Terminal 1 through the space between electric conductor layer and cryogenic cryostat.

- Liquid nitrogen then exits from Terminal 1 and flows into the cryogenic heat exchanger, equipped with cryogenic cold head, where the heat absorbed by liquid nitrogen during circulation is offset by the cryogenic output of the cooler.
- Liquid nitrogen is then pressurised by the liquid nitrogen pump and flows back to Terminal 1, where the process again repeats.

The general requirements of the cryogenic cooling system are as follows:

1. The nominal operational temperature of the LN2 is typically about 70 K. This sub-cooled liquid nitrogen operational temperature can reduce the formation of the nitrogen gas bubbles, which gets impregnated into the insulation layer causing a dielectric breakdown.
2. The liquid nitrogen circulates in the HTS cable cryogenic cooling path under the nominal operating pressure of 0.1 - 1 Mpa. The value of the operating pressure should be decided by taking the maximum allowable pressure for superconducting cable cryostat into consideration.
3. The flow rate of liquid nitrogen is typically over 25 kg/min. The value of flow rate will affect the heat transfer between the superconducting cable and liquid nitrogen.
4. The cryogenic system should be able to operate under normal conditions in a completely unattended mode with only regular maintenance. Frequent inspection is recommended so as to ensure the proper operating condition of the superconducting cable system.

4.5.2 Procedures of Superconducting Cable Cooling Down Process

The following procedures can be considered as guidelines for the superconducting cable cooling down process:

1. Cryostat leak testing

After completing the superconducting cable installation, a pressure test is to be performed, so as to ensure that there is no leak in the inner corrugated pipe of cable cryostat. The test can be performed by injecting pressurized dry nitrogen gas into the inner corrugated pipe for a certain amount of time. The pressure monitored should not be less than the designed value of liquid nitrogen circulating pressure.

2. Liquid nitrogen injection

The superconducting cable can be cooled down from the room temperature (~300 K) to sub-cooled liquid nitrogen temperature (~70 K) by injecting liquid nitrogen. To avoid the thermal shock, a cold evaporated nitrogen gas is injected into the superconducting cable before letting the direct injection of liquid nitrogen. The pressure of evaporated nitrogen gas and liquid nitrogen will be controlled, so as to maintain at nominal operating pressure level. Injection of Nitrogen gas prior to the Liquid Nitrogen will ensure that there is no air inside the cryostat, which if present, will create icing inside the cryostat.

3. Parameters to be monitored

The parameters to be constantly monitored when the cryogenic cooling system is being operated at its nominal condition are as follows:

- Temperature, liquid nitrogen flow rate and pressure at main interface of superconducting cable system, including termination, joints, pumps and cryocooler
- Liquid nitrogen level in the storage dewar
- Power consumption of cryocooler

4. Vacuum leak testing

The parameters recorded in step 3 can be used to obtain the thermal loss of the superconducting cable without actually energising it. If the actual operating thermal loss is significantly larger than the designed value, then there is a possible damage to the cryostat vacuum section during cable installation, which results in heat invasion from ambient room temperature. The leak rate of tracer gas (helium) to the vacuum area through the outer and inner vacuum wall of cryostat can be detected by a helium leak detector.

4.6 Repair Procedures and Requirements

In the case of fault being occurred in the superconducting cable, proper repair procedures are essential. This section provides the repair procedures and requirements for superconducting cable system in response to the fault. The faults covered in this section includes: cryogenic cooling system and superconducting cable faults.

4.6.1 Repair to Cryogenic Cooling System

The comprehensive reasons for the cryogenic cooling system faults are very difficult to predict. In general, the possible reasons of fault can be categorised as follows:

1. Cryocooler malfunction
2. LN2 circulation pump malfunction
3. Thermal insulation breakdown

4.6.1.1 Repair to Cryocooler

In the case of the cryocooler malfunctioning, the backup cryocooler will take over the load and continue to keep the superconducting cable at nominal operational temperature until the fault is cleared. The superconducting cable can continue to serve the grid under this fault condition.

4.6.1.2 Repair to LN2 Circulation Pumps

In the case of pumps malfunctioning, the backup pumps should take over and provide pressurised circulation of liquid nitrogen in the superconducting cable, until the fault is cleared. In this case also, the superconducting cable can continue to serve in the grid, even under the fault condition.

4.6.1.3 Repair to Thermal Insulation Breakdown

The thermal insulation of superconducting cables is achieved by cryostat, which consists of a vacuum section between the inner and outer corrugated pipe. A superinsulation layer is wound on the inner wall of corrugated vacuum pipe to reduce the heat invasion from the ambient room temperature environment. The thermal insulation breakdown of superconducting cable could be possibly due to the damage or puncture of the following:

i. The outer wall of corrugated vacuum pipe, which leads to vacuum breakdown.
ii. The inner wall of corrugated vacuum pipe, which leads to loss of circulation pressure and liquid nitrogen.
iii. Both inner and outer corrugated vacuum pipe.
iv. A superconducting insulation layer, which leads to heat invasion to the superconducting cable cryogenic pipe.

In the case of substantial liquid nitrogen leak, being detected by the monitoring system, the aforementioned (i) to (iii) damages to the cryostat could have possibly occured. The damaged section should be located and the relevant superconducting cable section should be replaced. The following procedures could be considered as the guidelines in the case of the thermal insulation breakdown.

i. Remove the superconducting cable immediately from service using the switchgear
ii. Gradually warm the whole superconducting cable system to ambient temperature by the injection of nitrogen gas. It should be noted that air should not be injected into the cable to avoid severe icing.
iii. Locate the damaged section and cut the superconducting cable
iv. Replace the damaged cable with new cable using the superconducting cable joints.
v. Perform the cryostat leak test as mentioned in section 5.2.
vi. Cool down the superconducting cable to nominal operating temperature and restore liquid nitrogen circulating pressure.
vii. Connect the superconducting cable back to grid and restore it to service.

4.6.2 Repairing Superconducting Cables

Superconducting conductors in the cable will not get damaged when subjected to a fault with a nominal maximum magnitude, and the conductors cannot be damaged if the maximum magnitude fault is cleared within the nominal duration. However, the superconducting conductors are vulnerable to get damaged under faults with magnitudes and/or clearing times beyond the identified values.

The superconducting electrical insulation could get damaged when subjected to a fault voltage exceeding the maximum value.

If the damage to the superconducting conductors and/or electrical insulation happens, the faulty section should be located and replaced with a new small section of superconducting cable using the two cable joints, thus following the same procedures as described in section 1.6.4.

In general, the repair of superconducting cable is far more complicated than conventional cable due to its complex configuration and there are no standard repair procedures for superconducting cable. Hence, the repair of superconducting cable cannot be performed by normal trained electrical technicians. The superconducting cable manufacturers should be responsible for the repair. On the other hand, because superconducting cable needs to be warmed up to room temperature during the repair process and cooled down to operational temperature to serve back again in the grid, it normally requires significantly longer time to complete the whole repair process.

4.7 Lifetime Assessment

There is no degradation in the superconducting properties of the superconducting materials upon their long term operation [16]. The major reasons of degradations could be thermos-cycling (the cycle that superconductor is cooled from room temperature to cryogenic temperature and warming back to room temperature) of superconducting tapes. However, modern superconductors do not degrade unless the cycles are more than 200. The real superconducting cable installation project will only have one thermal cycle unless essential repair requires warming up the superconducting cable to room temperature.

Therefore, the expected lifetime of superconducting cables is more than 40 years based on cable manufacturer specification details [16].

4.8 Health and Safety Considerations of Superconducting Cable Systems

Liquid nitrogen is environmentally friendly, however, there are still some hazards, which are needed to be taken into account for superconducting cable applications.

Superconducting cable systems require a large quantity of liquid nitrogen usage and storage requirements, especially for the open loop cooling system. The major health and safety issue comes from hazards and risks associated with the use of liquid nitrogen. This section is intended to provide such hazards information and the safety procedures.

4.8.1 Main Hazards of Liquid Nitrogen

Liquid nitrogen is a colourless, odourless liquid with a boiling point of -196°C (77 K). At low temperatures, the gas or vapour is heavier than air. Small amounts of liquid can vaporize rapidly to produce large volumes of gas. Typically, 1 litre of liquid nitrogen will produce 0.7 m3 of gas. Nitrogen gas is invisible, but the cloudy vapour which appears when liquid nitrogen is exposed to air is condensed moisture, not the gas itself.

There are two broad types of hazards arising from liquid nitrogen. The hazards related to temperature are cryogenic burns and frostbite and the hazards related to vapour is asphyxiation.

4.8.1.1 Cryogenic Burns and Frostbite

Liquid nitrogen can cause cryogenic burns if the substance itself, or surfaces which are in contact with the liquid nitrogen (e.g. metal transfer hoses) comes into contact with the skin. Local pain may be felt as the skin cools, though intense pain can occur when cold burns thaw and if the area affected is large enough, the person may even go into shock depending on the intensity of burn. Continued exposure of unprotected flesh to liquid nitrogen can result in frostbite. There is usually sufficient warning by local pain whilst the freezing action is taking place.

4.8.1.2 Asphyxiation

Although liquid nitrogen evolves nitrogen gas which is inert and non-toxic, there is a risk of asphyxiation (oxygen deficiency), in the case where high concentrations of nitrogen gas may accumulate and subsequently displace oxygen from the room. Liquid nitrogen expands around 700-fold when it vaporises at room temperature, in other words, 1 litre of liquid produces nearly 700 litres of gas. Closed vessels containing liquid nitrogen may explode because of the build-up of pressure caused by the evaporation. In poorly-ventilated rooms, there is a hazard that air will be displaced by the nitrogen, resulting in an oxygen-deficient atmosphere. Short exposures to cold gas vapour leads to discomfort in breathing whilst prolonged inhalation can cause serious effect on the lungs and could possibly provoke an asthma attack or even death by asphyxiation. Persons working in an atmosphere that is becoming oxygen deficient are unlikely to be aware of the increasing danger. But there are few warning signs that may be present for perception and judgement resulting from the reduced oxygen levels. The general effects of oxygen level less than 21 % by volume in the atmosphere are given in the table below:

Oxygen Content (vol. %)	Effects and Symptoms (at atmospheric pressure)
20 - 14	Diminution of physical and intellectual performance without person's knowledge.
14 - 10	Judgement becomes faulty. Severe injuries may cause no pain. Ill temper easily aroused. Rapid fatigue on exertion.
10 - 6	Nausea and vomiting may appear. Loss of ability to move vigorously or at all. Inability to walk, stand or crawl is often first warning and it comes too late. Persons may realise they are dying but does not care. Resuscitation possible if carried out immediately.
0 - 6	Fainting almost immediate, painless death ensues, brain damage even if rescued.

Table 4.5: The general effects of reduced oxygen level [33]

4.8.2 Safety Procedures

This section is intended to provide information on the hazards and risks associated with the use of liquid nitrogen and the control measures which can be used. In many cases, additional local information will be required to cover the particular circumstances in which liquid nitrogen is being used within facilities. This information should be supplemented by appropriate training and demonstration where specific tasks are undertaken.

4.8.2.1 Personal Protective Equipment (PPE)

For hands protection, non-absorbent insulated gloves must always be worn when handling anything that is or has been in recent contact with liquid nitrogen. Cryogenic gloves are designed to be used in the vapour phase only and should not be immersed in liquid nitrogen under any circumstances. They should be a loose fit to facilitate easy removal. Gauntlet style gloves are not recommended for some liquid handling uses as the liquid can drip into them and become trapped against the skin - sleeves should cover the ends of gloves or alternatively, a ribbed cuff style may be used. For face protection, a full face mask should be used to protect the eyes and face where splashing or spraying may occur and, in particular, where operations are carried out at eye level e.g. when topping up reservoirs on electron microscopes. For body protection, a laboratory coat or overalls should be worn at all times. Open pockets and turn-ups where liquid could collect should be avoided. Trouser bottoms should overlap boots or shoes for the same reason. For feet protection, sturdy shoes with a re-enforced toe-cap are recommended for handling liquid nitrogen vessels. Open toed shoes should not be worn under any circumstances. [34]

4.8.2.2 Storage and Ventilation

The dangerous results are usually from asphyxiation, caused due to the displacement of air by nitrogen gas. Hence, ample natural ventilation is required. If the superconducting cable installation adopts the open loop cooling system, bulk liquid nitrogen storage is required onsite. Indoor installation for such large size of dewars is difficult for ventilation. However, outdoor installation is an advantage due to ample natural ventilation. Outside the building, liquid nitrogen dewars should be stored inside an enclosure with mesh walls, as shown in the following figure.

Figure 4.17: Outdoor secure liquid nitrogen storage [35]

Storage inside the building is more of safety concern and superconducting cable cooling system requires a relatively small quantity of liquid nitrogen storage inside the building to engage with a heat exchanger. Hence, it is inevitable to consider indoor liquid nitrogen safety issues. The greatest danger is in the morning because there could have been significantly build-up of nitrogen gas overnight and especially over the weekend. Although the oxygen deficiency is unlikely to be hazardous under normal conditions there is still uncertainty about abnormal conditions, for instance, the degradation of insulation resulting in an unexpected release of gas.

In order to prevent any liquid nitrogen related accidents, wherever possible, liquid nitrogen should be stored in rooms having good natural ventilation. If this is not possible, the room must have forced ventilation of at sufficient level. The room must have an oxygen deficiency alarm installed inside the room. The alarm signal must be audible or visible from outside the room, alarm malfunctions must be visible or audible from outside the room and the alarm must be checked periodically following the manufacturer's recommendations. The following figure shows Nexans AmpaCity project indoor liquid nitrogen storage facility.

Figure 4.18: Nexans AmpaCity project indoor liquid nitrogen storage

4.8.2.3 Emergency Procedures

In the event of large liquid nitrogen spillage or accidental release, the following procedures should be followed:

- Evacuate the area. Deploy warning signs if necessary.
- Ventilate the area. Open doors and windows or activate forced ventilation to allow any spilt liquid to evaporate and the resultant gas to disperse.
- Try to stop the release if at all possible, e.g. turn off valves, but only if it is safe to do so, always wear protective clothing.
- Do not re-enter area unless it is proved safe to do so. The presence of oxygen deficiency monitors will indicate the oxygen levels in the vicinity.
- Prevent liquid nitrogen from entering drains, basements, pits or any confined space where accumulation may be dangerous.

4.9 Capital and Operational Costs

This section presents the costs of a completed superconducting cable system, including the capital investment costs and operational costs. The capital investment costs provide the indicative expected cost of each essential component (superconducting materials, cryogenic cooling system and other auxiliary equipment) in the superconducting cable system and the costs are produced based on the information obtained from experienced superconducting cable manufacturers. The operational cost will provide the maintenance cost when the superconducting cable is in the service, which is based on the data from the previously superconducting cable project that is currently in service.

4.9.1 Capital Cost Estimation

To give an indication of the total cost of a completed superconducting cable system, initial estimates have been produced for 11kV, 33kV and 132kV cables with identical ratings to conventional cables, currently being used by Western Power Distribution. These estimates have been produced by employing the following method:

The capital investment cost of a complete superconducting cable system can be categorised into three main parts:

i. Superconducting material,
ii. Cryogenic cooling system and
iii. Auxiliary equipment.

The superconducting material, being the most expensive component in the entire system, has varied costs from supplier to supplier. For example, the expensive superconducting tape could be about £ 58 per meter, while the cheap superconducting tapes could be about £ 30 per meter. According to superconducting cable manufacturers [16], the cost of a completed superconducting cable project can be estimated by the individual contributions of its various components with the following approximate ratios:

- The superconducting tapes contribute to 30 % of total capital cost based on the current rating and length of the cable.
- The cryogenic cooling system, including cryostat, termination, joints and cryocooler, contributes to 30-35 % of total capital cost based on the cable voltage rating.
- The remaining 35%-40% is contributed by all other costs, including auxiliary and control equipment.

Based on the superconducting cable cost estimation methodology, the cost of superconducting cable with different ratings can be estimated. Taking the 11 kV/ 905 A/ 1 km superconducting cable as an example, the cost estimation can be made by considering the cost of total superconducting material required for the given rated current, and extrapolating it to the complete cable by the appropriate percentage. Typically, the maximum current of the commercially available superconducting tapes is of 100 A. Hence, considering a safety margin of 1.4, 905 A rating requires superconducting cable to have 1267 A critical current. 11 kV superconducting cable will adopt triaxial configuration, so 1 km three phase superconducting cable requires total number of superconducting tape is 26. Hence, the total length of superconducting tape required is 79,050 m. Now, considering the price of superconducting tape, since it varies with different suppliers, the typical price margin is between £ 22 to £ 58 per meter depending on manufacturers. Therefore, the total cost of superconducting material is estimated to be £ 1.74 million to £ 4.58 million.

Considering the cost distribution of each component of the completed superconducting cable system, (i.e. 30 % for superconducting material, 30 % to 35 % for cryogenic cooling system, and 30 to 35 % for all other cost) the cost of cryogenic cooling system could be estimated to be £ 2.22 million and all the other costs to be £ 2.02 million. Hence the total cost of a completed 11 kV/905 A/1 km superconducting cable system can be estimated to be in the range of £ 5.97 million to £ 8.82 million.

It should be noted that the aforementioned cost estimation methodology is a rough estimation based on the experience of superconducting cable manufacturers. This estimation may be different from the cost provided by manufacturers from an official tender process due to a number of varied factors, which include but are not limited to: choice of superconducting materials, length of cables ordered, choice of cooling system and willingness of manufacturers to take the project. But still, this estimation methodology can provide a useful ballpark figure to start a feasibility study. This method has been compared with a preliminary quote from a manufacturer and shows that the two prices are in the same order of magnitude and broadly consistent. Details can be found in section 4.9.2.

Table 4.6 and Table 4.7 provide the estimated cost of superconducting cables for a length of 1 km and for varied voltage ratings of 11, 33 and 132 kV based on the method above. The ratings are selected in such a way, so as to provide a direct comparison with conventional cable being used by WPD. The specifications of these conventional cables are used in providing the rough estimated cost of the relevant superconducting cables.

Voltage (kV)	Current Winter Sustained (A)	Length (km)	Capacity (MVA)	Superconducting Tape (m£)	Cryogenic Cooling System (m£)	Auxiliary/Control (m£)	Total Cost (m£)
33	475	1	27	0.94 ～2.49	1.31	1.31	3.35～4.90
33	620	1	35	1.21～3.19	1.69	1.69	4.30～6.29
33	705	1	40	1.37～3.61	1.91	1.91	4.86～7.10
33	905	1	52	1.74～4.58	2.42	2.42	6.17～9.02
11	380	1	7	0.77～2.03	0.89	0.98	2.64～3.90
11	495	1	9	0.98～2.59	1.14	1.25	3.37～4.97
11	635	1	12	1.24～3.27	1.44	1.58	4.26～6.29
11	720	1	14	1.40～3.68	1.62	1.78	4.80～7.08
11	905	1	17	1.74～4.58	2.02	2.22	5.97～8.82

Table 4.6: Capital investment of 11 kV & 33 kV superconducting cables

Voltage (kV)	Current Winter Sustained (A)	Length (km)	Capacity (MVA)	Superconducting Tape (m£)	Cryogenic Cooling System (m£)	Auxiliary/Control (m£)	Total Cost (m£)
132	458	1	105	1.82～4.81	3.18	2.12	7.12～10.10
132	526	1	120	2.08～5.47	3.61	2.41	8.10～11.49
132	587	1	134	2.30～6.07	4.00	2.67	8.98～12.74
132	658	1	150	2.56～6.76	4.46	2.97	10.00～14.20
132	734	1	168	2.84～7.50	4.95	3.30	11.09～15.75
132	811	1	185	3.13～8.25	5.45	3.63	12.20～17.33
132	884	1	202	3.40～8.96	5.91	3.94	13.26～18.82
132	949	1	217	3.64～9.60	6.33	4.22	14.19～20.15
132	964	1	220	3.69～9.74	6.43	4.29	14.41～20.46
132	1012	1	231	3.87～10.21	6.74	4.49	15.10～21.44
132	1059	1	242	4.05～10.67	7.04	4.69	15.78～22.40
132	1115	1	255	4.25～11.21	7.40	4.93	16.59～23.55
132	469	1	107	1.87～4.92	3.25	2.16	7.28～10.33

Table 4.7: Capital investment of 132 kV superconducting cables

4.9.2 Capital Investment Cost of Superconducting Cable Supplied from Superconducting Cable Manufacturer and Previously Installed Superconducting Cable Projects around the World

Table 4.8 below is the latest capital investment cost of superconducting cables provided by superconducting cable manufacturers. Table 4.9 provides the costs of previous superconducting cable projects.

	11 kV/ 2000 A	33 kV/ 2000 A
Price per kilometer	£ 4,965,000	£ 6,150,000

Table 4.8: Latest price information for the superconducting cable

In general, the capital investment cost of a completed superconducting cable is a one-off cost and varies from supplier to supplier due to the following factors:

- The price of raw materials to be made into superconductors varies from different suppliers.
- The price of cryogenic cooling system varies from different suppliers and also depends on the selection of cooling methods.
- The labour cost of superconducting cable manufacturers varies.

However, compared with the latest superconducting cable cost provided by the manufacturer in Table 4.8 and previous superconducting cable project cost in Table 4.9, it is clear to see that the costs have been reduced significantly compared with previous demonstration projects. It should also be noted that the cost in Table 4.8 is a preliminary cost from superconducting cable supplier, which might further be reduced in an actual tendering process.

Project	Type/Year	Location	Project Cost (m£)	Remarks
Long Island project	138 kV/2.4 kA/ 600 m/2008	Long island, New York, US	34.90 [10]	World's first transmission voltage superconducting cable
AmpaCity project	10 kV/ 2 kA/ 1000 m/2014	Essen, Germany	11.17 [28]	World's longest superconducting cable
Hydra project	13.8 kV/ 4.0 kA/ 300 m/2013	Manhattan, US	29.25 [29]	Interconnection between substations
DC superconducting cable project	+/- 10 kV/2 kA/ 1000 m/2016	China	10.99 [27]	World's longest DC superconducting cable
Columbus HTS Triax Project	13 kV/ 3 kA/ 200 m/2008	Columbus, Ohio, US	8.78 [30]	Provided the link from a 138 kV - 13 kV step-down transformer to a 13 kV substation

Table 4.9: Previous superconducting cable projects costs

4.9.3 Operational Costs

For the superconducting cable system, the operational cost is mainly coming from the liquid nitrogen consumption and the electricity supply at nominal operation. The liquid nitrogen consumption varies based on the cable length and thermal losses, while the electricity consumption comes from the cryocooler, liquid nitrogen circulation pump, and vacuum pump.

For Nexans AmpaCity superconducting cable (10 kV/2 kA/1000 m), in the nominal operation of the superconducting cable system, it is mentioned that it requires an electricity consumption of 160 kWh per day and a daily liquid nitrogen consumption of about 2000 kg [31]. Considering the cost of liquid nitrogen at about 20 p per kg and the cost of electricity at about 10 p per kWh, then the operational cost of AmpaCity superconducting cable is calculated to be about £ 416 per day.

Figure 4.19 gives the liquid nitrogen and electricity consumption of a 1 km superconducting cable in terms of cooling capacity demand. It can be concluded that the operational cost is almost linearly increasing with the cooling power demands, which primarily depends on the length and total power being transferred by the superconducting cable.

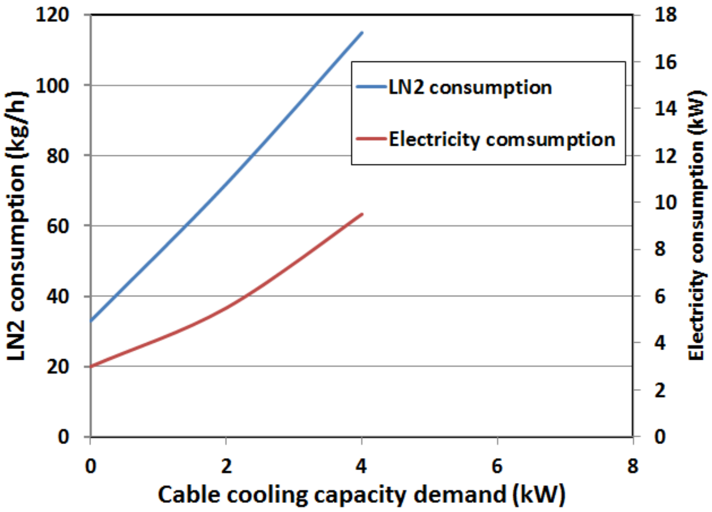


Figure 4.19: Liquid nitrogen (LN2) and electricity consumption of a completed 1 km superconducting cable system [47]

Chapter 5

Conventional Cables Solution

5.1 Introduction to Chapter 5

Following the investigation of the key aspects of superconducting cable systems, this chapter examines the conventional cable implementations, covering the same areas as Chapter 4. This will provide all the comprehensive information required for performing a detailed comparison of the two solutions (i.e. superconducting cable vs conventional cable) in Chapter 6.

- Mechanical configuration and physical description
- System components and requirements
- Installation procedures and requirements
- Operational procedures and requirements
- Repair procedures and requirements
- Lifetime assessment
- Capital and operational costs

5.2 Mechanical Construction and Physical Description

5.2.1 General Description of Conventional Cables

The design of conventional cables should confine to the well-established international standards of IEC 60502 and IEC 60840. Conventional cables rated at 11 - 132 kV have, in general, circular conductors and only single core construction. Conductors may be of compacted stranded aluminium or stranded copper. Special care should be taken in order to ensure a smooth surface profile of conductors; as sharp juts could damage the insulation due to high localised electrical stresses. The extruded cross-linked semiconducting screens are laid on the conductor, to protect the main XLPE/EPR insulation.

Considering the insulation material used for conventional cable, XLPE-insulated cables have a rated maximum conductor temperature of 90 °C and an emergency rating of up to 140 °C, depending on the standard used. They also have a conductor short-circuit rating of 250 °C [36]. Similarly, EPR-insulated cables are rated up to 105ºC for normal operation, 140ºC for emergency operation and 250ºC for short circuit [37]. Figure 5.1 shows the configuration of conventional XLPE/EPR cable.

5.2.2 XLPE/EPR Cable Configuration and Description of each Component

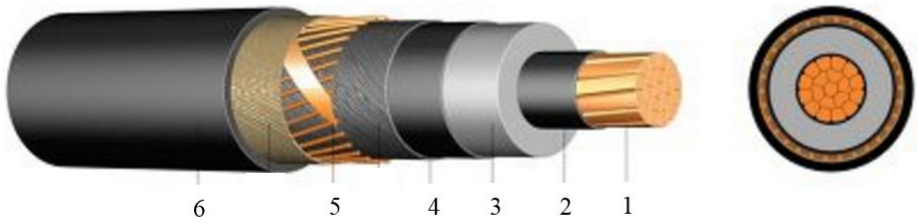


Figure 5.1: Configuration of XLPE/EPR cable

XLPE cables consist of the following components and Table 5.1 describes main function of each component.

1. Conductor Copper (Cu) or Aluminium (Al)
2. Internal semiconductor
3. Insulation
4. External semiconductor
5. Metallic screen
6. Non-metallic outer sheath PE

Item	Functions	Composition
Conductor	• To carry current ✓ under normal operating conditions ✓ under overload operating conditions ✓ under short-circuit operating conditions • To withstand pulling stresses during cable laying	• Area < 1000 mm^2 (copper or aluminium) Compacted round stranded conductors • Area < 400 mm^2 (aluminium) Round solid conductors
Internal semiconductor	• To prevent concentration of electric field at the interface between the insulation and the internal semiconductor • To ensure close contact with the insulation. • To smooth the electric field at the conductor.	Semi-conducting shield
Insulation	• To withstand the various voltage	XLPE or EPR insulation

Item	Functions	Composition
	field stresses during the cable service life: ✓ rated voltage ✓ lightning overvoltage ✓ switching overvoltage	
External semiconductor	• To ensure close contact between the insulation and the screen. • To prevent concentration of electric field at the interface between the insulation and the external semiconductor	Semi-conducting shield
Metallic screen	• To provide: ✓ An electric screen (no electric field outside the cable) ✓ Radial waterproofing (to avoid contact between the insulation and water) ✓ An active conductor for the capacitive and zero-sequence short-circuit current ✓ A contribution to mechanical protection	Extruded lead alloy, or Copper wire screen
Outer protective sheath	• To insulate the metallic screen from the surrounding medium • To protect the metallic screen from corrosion • To contribute to mechanical protection • To reduce the contribution of cables to fire propagation	• Insulating sheath ✓ PE jacket ✓ PVC jacket

Table 5.1: Summary of the mechanical and physical descriptions of XLPE cable [38]

5.3 System Components and Requirements

5.3.1 Cable Termination-Conventional Cable to Power Grids

The function of the conventional cable terminations is to provide a good electrical connection of the cable to the networks. The termination's main challenges are to provide electrical stress control, which can be implemented by a cone or stress distribution materials, and the core connector, such as cable lugs. The cold-shrinkable terminations are recommended on single core and three core 11 and 33 kV conventional cables, for its use of both in indoors and outdoors. By using cold-shrinkable terminations (a stress distributing material), controls the electrical field, which will only slightly increase the outer diameter of the cable. The cold-shrinkable termination techniques of conventional cable are standardized and can be ordered from various suppliers. Considering the possible suppliers of conventional cable terminations within the UK, the following types of cold shrink terminations can be considered:

1. The Tyco cold shrink cable terminations are suitable for the 11 kV conventional cables for both indoor and outdoor terminal installation.
2. The 3M cold shrink cable terminations are suitable for the 33 kV conventional cables for both indoor and outdoor terminal installation.

These types of terminations can provide the following benefits:

- Excellent cold shrink electrical insulating performance
- Hydrophobic properties - water and moisture resistant
- Excellent high and low-temperature operation
- Non-flammable silicone rubber Cold Shrink termination
- One-piece cable termination for quick installation
- Built in cold shrink stress control for reliable service
- Compact design for limited working access in cable end termination boxes

Table 5.2 and Table 5.3 summarize the termination techniques being employed for 11 kV and 33 kV conventional cables with different cross-section areas. Similarly, Figure 5.2 gives the schematic of indoor and outdoor terminations.

Cable Types	Termination Techniques
185/300mm² Cu single core	3M - 94-EP631-2-WPD Cold shrink - Indoor
400/630mm² Cu Single core	3M - 94-EP641-2-WPD Cold shrink - Indoor
185/300mm² Cu single core	3M - 94-EP631-2-WPD Cold shrink - Outdoor
400/630mm² Cu Single core	3M - 94-EP641-2-WPD Cold shrink - Outdoor

Table 5.2: 33 kV cable termination techniques [40]

Cable Types	Termination Techniques
185/300mm² SAC Triplex	Tyco CSTI-3131-GB01 Cold shrink - Indoor
400/630mm² Cu Single Core	Tyco CSTI-3141-GB01 Cold shrink - Indoor
185/300mm² SAC Triplex	Tyco CSTO-3131-GB01 Cold shrink - Outdoor
400/630mm² Cu Single Core	Tyco CSTO-3141-GB01 Cold shrink - Outdoor

Table 5.3: 11 kV cable termination techniques [40]

(a) Indoor termination (b) Outdoor termination

Figure 5.2: Schematic of indoor and outdoor terminations

5.3.2 Cable Joint-Conventional Cable to Conventional Cable

Cable joints are to be used to provide electrical and dielectric insulation continuities for all the cable and similarly to provide the mechanical protection and strength. Cable joints are necessary when the electrical transmission distance required is not possible to be achieved by a single cable. The structure of cable joints is made according to the specification details required at the site. The straight through joints are the mostly used type of joint to extend pieces of electrical cable for the 11 kV and 33 kV conventional cables. Straight joints can be widely used in various environments, including indoor, outdoor, submerged and underground cable jointing. The cable joints should provide reliable electrical and dielectric insulation connection between the corresponding 3 phase individual cables inside the main cable. Since the majority of the cable joints are to be installed in the underground space, the joints should be properly sealed to prevent any moisture leakage. There are several standard types of cable joints from the manufacturers, considering the possible suppliers of conventional cable joints within the UK, the following types of straight through joints can be considered for 11 kV and 33 kV cable:

1. Lovink LoviSil K straight through cable joint is suitable for 11 kV cable.
2. Raychem heat shrink straight through cable joint is suitable for 33 kV cable.

These types of straight through cable joints can provide the following benefits [41]:

- Minimising the risk of discharge or dried out insulating material.
- Providing consistently homogeneous electrical field.
- Creating a seal that prevents any further ingress of moisture.
- Providing universal earth connection.
- Can be ordered on the basic of modular system.

Table 5.4 and Table 5.5 summarize the straight through joints types for 11 kV and 33 kV conventional cables with different cross-section areas. While, Figure 5.3 depicts the heating process that the Raychem heat shrink straight joint undergoes during the installation of the joint of conventional cables.

Cable Types	Joint Techniques
11 kV 185 mm^2 SAC triplex	Lovink cold applied K 85 straight joint
11 kV 300 mm^2 SAC triplex	Lovink cold applied K 95 straight joint
11 kV 400 mm^2 Cu triplex	Lovink cold applied K 95 straight joint
11 kV 630 mm^2 Cu single core	Lovink cold applied K 75 straight joint

Table 5.4: Cable joints for 11 kV cable [40]

Cable Types	Joint Types
33 kV 185 mm^2 SAC triplex	Raychem heat shrink straight joint
33 kV 300 mm^2 SAC triplex	
33 kV 400 mm^2 Cu triplex	
33 kV 630 mm^2 Cu single core	

Table 5.5: Cable joints for 11 kV cable [40]

Figure 5.3: Raychem heat shrink cable joint

5.3.3 Cross Bonding Link Boxes

Conventional cables laid out in power grid carry AC current and induced voltages in the metallic sheath of the cable during operation. Depending the sheath bonding, this would result in circulating currents flowing in the cable sheath, which eventually reduces the transmission capacity of the cable and causes additional heating. Cross bonding link boxes are used for grounding and bonding cable sheaths, so that the induced voltages and circulating currents are eliminated or reduced.

The cross bonding link boxes are standardised and are available from various power cable accessory suppliers in the UK. The key challenge of using cross bonding link boxes in the conventional system is the installing locations along the cable, in order to realise:

- No circulating current so that transmission efficiency can be improved.
- No heating in the cable screen so that transmission capacity can be improved.

By applying cross bonding link boxes in the conventional cable system, the electrical power transmission can be very economic. When the link boxes are installed in the ground, the length of the bonding leads which connect the joints to the link boxes must not exceed 8m. This means that if the circuit is laid in the carriageway then the cross bonding link boxes can be installed in the sidewalk; this will allow future maintenance on the link boxes without having to get a lane closure, as shown in Figure 5.4.

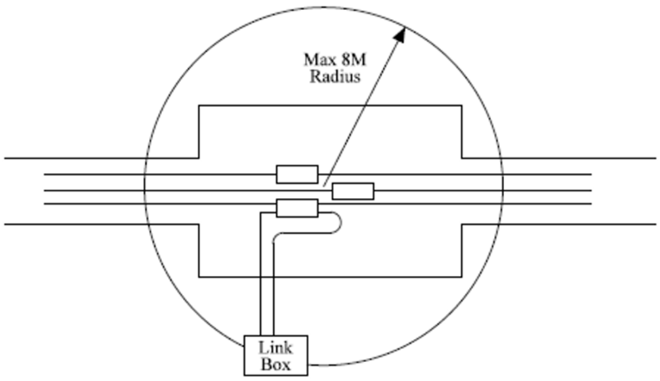


Figure 5.4: Schematic of cross bonding link boxes [39]

5.3.4 Cable Ties for Triplex/Trefoil Cable Configuration

When using trefoil configuration for conventional cable installation, 13 mm wide cable ties are placed on the leading 5 m to 7 m of cable, to prevent the unwinding of the cable prior to the cable being laid. If this cable is then to be pulled into ducts, the cable ties should be taped over with Scotch 88 tape to prevent the cable ties snagging on the ducts and the cable shall be tied to the bond at not more than 2 m intervals along its entire length. Where large diameter cables are to be installed, or the cables are to be installed on a steep incline or down a shaft, the number of ties is to be increased. Figure 5.5 shows the cable laid in trefoil configuration and tied at 1.5 m interval [39].

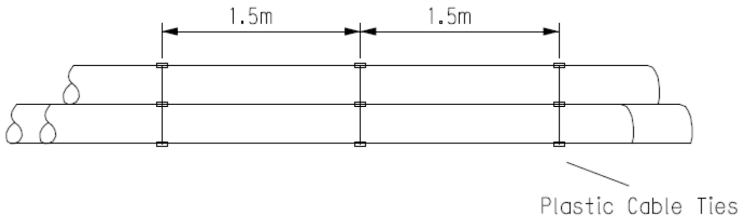


Figure 5.5: 33, 66 and 132 kV cables laid in trefoil configuration and tied at 1.5 m interval

5.4 Installation Procedures and Requirements

5.4.1 Type of Installation

During the installation process, conventional cables can be laid directly in the trench, or pulled into the cable ducts in the underground space. Flat and Trefoil configurations are the two mostly used types of installation for conventional cables.

Typically, trefoil configuration is more commonly used for conventional cable up to 132 kV due to its ease of installation processes and reduction in space required. Therefore, the flat configuration is not considered in the distribution network and cables under 132 kV should be laid in a trefoil formation.

For 11 kV conventional cables, there is an adaptation of the trefoil formation technique that can be used, called triplex configuration. Triplex cables are three conventional single-core cables supplied pre-wound in the trefoil configuration by the cable manufacturers. The three cable cores having been slowly twisted together during the manufacturing process and supplied on one drum, offering significant benefits in installation time reduction.

However, installing conventional cables in trefoil configuration can mean that the touching cables will experience worse heat-dissipation when compared to flat configuration. Therefore, lowering the current-carrying capacity. By using trefoil configuration, if the heat-dissipation affects the current capacity significantly, then the flat configuration should be considered.

5.4.2 Cable Drum Transportation and Handling

Conventional cables are to be transported to the installation site by cable drum, which can be provided by cable suppliers. During the cable installation, the drum's rotation should be controlled and the stability of the drum and jacks is to be monitored. The drum should be positioned so that the pull from the drum to the trench is as straight as possible. During the entire installation process, the lead in the angle of the cable to the trench should not exceed the maximum allowable angle. A lead-in roller shall always be used to guide the cable into the trench. While pulling the cable into the duct, the drum should be positioned above the duct, so that the cable leaves the drum and enters the duct in a smooth fashion. The drum can be rotated by hand during the installation, so as to ensure that the cable between the drum and the duct mouth doesn't undergo huge tension. This entire procedure is very much similar to the superconducting cable drum handling.

5.4.3 Trenches, Pipes, and Ducts

The trenches are used for conventional cables for directly laying down in the underground space. If additional protections are required, such as preventing conventional cables from flood, pipes and ducts can be implemented in the underground space, and the cable can be pulled into the pipes and ducts accordingly.

The maximum bending diameters of trenches, pipes and ducts shouldn't exceed the specified limits of the maximum bending diameter of conventional cable as given in Table 5.6. Otherwise, it will cause damage to the cable insulation and cable screening systems, resulting in premature failure.

The pipes and ducts should be kept as straight as possible to ease the complexity of cable pulling process. However, since the pipes and ducts can cause de-rating to conventional cable as the heat-dissipation cannot be removed efficiently, the maximum length of pipes and ducts to be used should be based on this de-rating influence to ensure the efficiency of electrical transmission.

Cross Section Area	185mm²	300mm²	400mm²	630mm²
	Minimum radius of bend, along which cable can be laid:			
Laid direct or in air	0.85 m	0.95 m	1.02 m	1.2 m
In ducts	0.85 m	0.95 m	1.02 m	1.2 m
Adjacent to joints or terminations	0.65 m	0.75 m	0.8 m	0.9 m
Nominal internal diameter of duct	150 mm	150 mm	150 mm	100 mm

Table 5.6: Maximum bending diameters for conventional cable [39]

5.4.4 Cable Pulling

Conventional cables are normally pulled into the ducts or laid in the trench by a winch. When a winch is used, it should be fitted with a suitable dynamometer, which will be continuously monitored to ensure that the maximum pulling tension is not exceeded at any time. An appropriate pulling eye should be fitted with a pulling bond and the pulling attachment on the cable. If the pulling force exceeds the maximum allowed value, it will cause damage to the cable.

Since the superconducting cable manufacturers can supply a superconducting cable with comparable installation process with conventional cable, same aforementioned processes can also be extended to the superconducting cable when being pulled the cables into the ducts or laid in the trench.

5.4.5 Depth of Cover

Due to the thermal and electromagnetic impact of conventional cables, the depth of cover is the minimum depth under which a cable or a duct is supposed to be installed so as to protect it from environmental scour and third-party human activities. This depth of cover will vary depending on the kind of terrain and the sensitive nature of the equipment being installed as well. These values are usually stipulated by the concerning regulation body of that particular area or the installation company or sometimes as recommended by manufacturers. The minimum depth of cover required in the WPD is detailed as in Table 5.7. However, in certain situations, if it may not be possible to achieve the required minimum depth of cover, it will be necessary to minimise the length over which minimum depth is not attained. Since the trefoil installation configuration is applied to power cables that are lower than 132 kV in the distribution network of WPD, the depth of cover is defined as the distance from the upper cable to the ground surface, as shown in Figure 5.6.

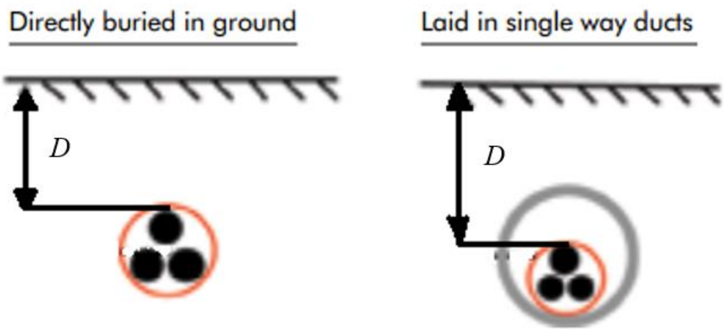


Figure 5.6: Schematic of depth of cover (D)

Surface Type	Voltage		
	11 k V	33 kV	66 kV
	Minimum depth of cover *D* (mm)		
Pavement or Private Road	750	750	900
Agricultural Land	1000	1000	1000
Roadway	520	750	900

Table 5.7: Minimum depth of cover requirements [39]

5.5 Operational Procedures and Requirements

Once the conventional cable is installed, before energising it is required to test the cable sheath and insulation integrity to ensure that there is no damage during the cable installation process. In other words, commission tests are required for new conventional cables that are going to serve in the power grids, which are the important operational procedures and requirements. Typical commission tests include the sheath testing and very low frequency (VLF) testing.

5.5.1 Sheath Testing

It is important for power cables to have a healthy sheath. However, the sheath is generally made of PVC or PE, which may be damaged during transportation and installation. Moreover, sheath faults may occur during normal operation due to mechanical forces, chemical erosion, termites or mice gnawing, etc [42].

On-site test procedure for polymeric cables incorporates a DC voltage sheath test. This test is to check that the primary protection for the cable i.e. to ensure that the oversheath has not been damaged during its installation. The sheath voltage test shall be carried out on each individual core. It is recommended to do the sheath test prior to joining, so that if there is a failure in the oversheath, the check for damage is restricted to a single drum length of cable. Once the damage site has been found, a sheath repair may be carried out and the circuit is re-checked. Table 5.8 shows the DC sheath test voltage level for all polymeric underground cable [43].

Circuit	Voltage Level - Sheath to Earth	Test Duration
Each phase - individually	5kV	5 minutes

Table 5.8: DC sheath test for conventional cables [44]

5.5.2 VLF Testing

VLF AC test is a commercially available electrical power test kit. This VLF test helps in detecting the potential failure modes in the cable insulation. Hence, once the conventional cables have been joined and are ready for final commissioning in the network, the cable should be tested on-site using the VLF AC test methods. The test frequency range depends on the load of the cable. This VLF test results help in making a critical decision of whether the cables can pass to serve in the network or not.

An example of the voltage levels to be applied to the 33 kV conventional cable under test is given in Table 5.9. It should be noted that the test voltage level varies with respect to the age of the oldest piece of cable in the circuit, which determines the testing voltage level [43]. Also a 30-minute testing period should be specified for new conventional cables because 89% of cable failures are likely to occur in the first 30 minutes.

Circuit	Voltage Level Phase to Earth	Test Duration
Each phase	47.5 kV	30 minutes

Table 5.9: VLF test for conventional cable [44]

5.6 Repair Requirements and Procedures

5.6.1 Possible Reasons of XLPE/EPR Cable Failures

Power cables can fail for a number of reasons, the most common causes being from external interference or damage, overheating, moisture ingress, poor accessory installation, cable or accessory defects, all of which will result in electrical failure or breakdown of the primary insulation. Identifying the real cause of a failure can be a difficult task, as one form of damage may lead to another, and the root cause may not be plainly evident. The following are the most common causes of conventional cable failure [45].

- Mechanical damage during cable installation.
- Ageing and overheating due to inaccurate system design, inappropriate installation, or abuse of the cable by overloading.
- Electrical deterioration due to partial discharge

5.6.2 Fault Repair of Conventional Cable

The fault repair of conventional cables generally involves identification and removal of the faulty section and the performing two straight joints on the healthy cable, then connecting the joints based on the instructions of joints supplier [46]. Because most of the underground cable systems are inaccessible, identifying the fault location can slow down the restoration process. Considering the lead times for replacement conventional cable and accessories, a conventional cable may require several days to weeks to repair, once the failure has been located and all necessary repair materials and electrical technicians are available.

5.7 Lifetime Assessment

XLPE/EPR Cables are expected to have a high lifetime of over 40 years, based on the data provided by WPD. The lifetime of a cable is defined as its operating time. It is influenced by the materials used, constructive design, production methods and the operating parameters.

The following rules are applied in predicting the lifetime of the conventional cable in general:

- An increase of the operating temperature by 8 to 10°C reduces the service life by half.
- An increase of the operating voltage by 8 to 10% reduces the service life by half.
- Other operating parameters which affect the conventional cable lifetime are as follows:
- Voltage level and transient voltages such as switch operations, lightning impulses

- Short-circuit current and related conductor temperatures
- Mechanical stress
- Ambient conditions like humidity, ground temperatures, chemical influences
- Rodents and termites in the vicinity

5.8 Health and Safety Considerations of Conventional Cable Systems

Faults occurring in conventional cables installed in the underground space are much less common when compared to overhead lines. But fault can of course occur, some of the following situations are such examples:

- Cut through by a sharp object such as the point of tool;
- Crushed by a heavy object or powerful machine such as digging.

When underground conventional cables are damaged, people can get injured by electric shock, electrical arcs (causing an explosion), and flames. This often results in severe burns to hands, face and body, even if protective clothing is being worn.

Damage to the underground conventional cable can cause fatal injuries and thus proper precautions should be taken to avoid any danger. Any civil excavation work should be properly managed to control the risks and always check with local DNO with the underground cable location.

5.9 Capital and Operational Costs

The capital investment cost of the conventional XLPE/EPR cable consists of mainly two parts:

i. XLPE/ERP cable
ii. Terminations and joints

It should be noted that the cost of labour for cable laying is not included in this cost. This is due to the reason of superconducting cables having the same cost of labour, as the laying process of conventional cables. Therefore, labour cost doesn't affect the cost differences between the superconducting cables and conventional cables.

Table 5.10 provides the cost per unit length (km) of 11 kV and 33 kV XLPE/EPR cables, currently being used by Western Power Distribution.

Voltage (kV)	Current winter sustained (A)	Length (km)	Capacity (MVA)	cable cost in £	termination and joint cost in £	total cable cost in £
33	475	1	27	39,210	1,919	41,129
33	620	1	35	60,030	1,919	61,949
33	705	1	40	70,380	2,347	72,727
33	905	1	52	111,270	2,686	113,956
11	380	1	7	14,320	1,038	15,358
11	495	1	9	18,130	1,279	19,409
11	635	1	12	51,460	1,155	52,615
11	720	1	14	64,310	1,155	65,465
11	905	1	17	96,450	1,781	98,231

Table 5.10: Capital investment of 11 kV & 33 conventional cables [40]

Chapter 6

Superconducting Cables and Conventional Cables – Cost Benefit Analysis

6.1 Introduction to Chapter 6

Based on the aspects presented in Chapter 4 (for superconducting cables) and Chapter 5 (for conventional cables), this chapter provides a detailed comparison between the superconducting cables and conventional cables, hence forming the Cost Benefit Analysis of Work Package 1.

6.2 Theoretical Benefits and Limitations

Superconducting cables have many unique benefits compared to conventional cables. The benefits of superconducting cables are:

1. Due to their high current density, Superconducting cables are capable of transmitting huge magnitudes of current with much lower losses, in a much smaller cable size. Utilities that want to transmit large currents requiring small rights-of-way will benefit from this technology.
2. There is no thermal and electromagnetic impact on the surrounding environment.
3. For electrical power transmission, using superconducting cables makes it possible to transmit huge power at a much lower operating voltage, hence removing the need of high voltage equipment (such as 132/11 kV transformers) and therefore reducing the overall investment cost.

However, there are also limitations for superconducting cable technology:

1. Continuous operation of cooling system is required as long as the superconducting cable is in service, which adds a significant amount to the power loss. Therefore, it is not economical to use superconducting cable for low current transmission.
2. It may cause power system instability, if the superconducting cable is integrated into the grid without power flow control methodologies, due to the extremely low impedance of superconducting cable.
3. Due to the high cost of superconducting material, the cost of superconducting cable is still very expensive compared with conventional cable.

Alternatively, using the traditional solution, the conventional cable can transmit electrical power with the following advantages:

1. The configuration of conventional cable is very simple and the technology is very mature.
2. The cost of conventional cable is very cheap when compared to superconducting cable.

However, there are many limitations for conventional cables:

1. Conventional cables require large right-of-way for high power transmission, which is extremely expensive in the urban city areas.
2. High voltage (132 kV) conventional cable electrical power transmission involves huge investment on the high voltage equipment cost.
3. There is a significant impact on the surrounding environment by using conventional cable, due to the thermal and electromagnetic fields emitted.

Table 6.1 gives the summary of the theoretical benefits and limitations of superconducting cables and conventional cables.

	Benefits	Limitations
Superconducting Cable	• High current capacity • Low voltage power transmission • Low losses • Small right-of-way • No thermal and electromagnetic impact	• Requires complex cryogenic cooling system • Low impedance may cause power system instability • Huge capital cost
Conventional Cable	• Simple design • Relatively low capital cost	• Low current capacity • Requires High voltage electrical transmission • Huge losses • Large right-of-way • Non-negligible thermal and electromagnetic impact

Table 6.1: Summary of theoretical benefits and limitations

6.3 Mechanical Construction and Physical Description

Superconducting cables irrespective of their operating voltage and current levels, are very compact with high current density, negligible losses. One superconducting cable per phase can meet high current capacities required to be transferred in UK electricity distribution networks. However, an appropriate cooling system is required for the reliable operation of the superconducting cable, which increases the solution's complexity. On the contrary, although the configuration of conventional cable is very simple, the overall current density is very small and has significant losses. Hence, multiple conventional cables per phase are always required for high current transmission (>1000 A).

Table 6.2 gives the summary of the mechanical construction and physical description of the superconducting cable and the conventional cable.

		Mechanical Construction and Physical Description	Remark
Superconducting Cable	Advantages	• compact cable size • high current density • low losses	A superconducting cable can have much smaller size to carry the same power of a conventional cable.
	Disadvantages	• Complex cable structure • Cooling system required	
Conventional Cable	Advantages	• Simple cable structure	
	Disadvantages	• Low current density • Significant losses	

Table 6.2: Summary of the mechanical construction and physical description

6.4 Installation Procedures and Requirements

The installation procedure of superconducting cables are not much different from conventional cables. Therefore, the installation method being employed for conventional cable can be directly used, to install the superconducting cables. Ideally, the installation requirements of superconducting cables are much simpler when compared to conventional cable. Particularly, trench dimension requirements of superconducting cable are much lower, mainly due to the absence of its thermal and electromagnetic impact on the surrounding environment. Additionally, compared with the minimum depth-of-cover required by conventional cable, superconducting cables requires less depth-of-cover, again due to the absence of any thermal and electromagnetic impact on the environment.

However, due to the complexity of superconducting cables compared with conventional cables, the installation processes of cable terminations and joints should be performed by specially trained electrical technicians or superconducting cable manufacturers themselves, while normal trained electrical technicians are capable and qualified enough to perform the whole installation of conventional cables.

Table 6.3 gives the summary of the installation procedures and requirements of the superconducting cable and the conventional cable.

	Installation Procedures and Requirements	Remark
Superconducting Cable	• requires much less underground space to install • special trained electrical technicians required.	Superconducting cables can save a significant amount of initial capital investment on expensive right-of-way cost in urban city.
Conventional Cable	• requires additional underground space to increase power transmission capacity • Normal trained electrical technicians required	

Table 6.3: Summary of installation procedures and requirements

6.5 System Components and Requirements

Terminations and joints are the main components of superconducting cable implementations as well as conventional cables. They should be able to provide the following basic functions: electrical and insulation continuity for separated cables and the protection of the cable cores.

However, the cable terminations and joints for superconducting cables are much more complex than for conventional cables. Hence, it is easier to joint conventional cables when compared to superconducting cables. Additionally, to joint a conventional cable, standardized termination and joint accessories are available from local supplier in the UK. However, for superconducting cable, extra components are required, which include cryogenic systems in the termination and joints. Compared with conventional cables, the termination and joints for superconducting cables are much more complicated and require a special design from manufacturers based on the requirements of NDOs, in order to provide electrical and insulation continuity as well as liquid nitrogen circulation and thermal insulation.

Cryogenic system is required only for superconducting cable, in order to make sure that the cable operates at the nominal temperature (77 K). The cooling system contains cryocooler, liquid nitrogen pump, cryogenic heat exchanger and liquid nitrogen storage Dewar.

Table 6.4 gives the summary of the system components and requirements of the superconducting cable and the conventional cable.

	System Components and Requirements	Remark
Superconducting Cable	• Complex cable terminations and joints • Require special design on cable termination and joints • Difficult to make terminations and joints	Superconducting cables require complex cable terminations and joints designs and additional cryogenic cooling system. These should be performed by specialised engineers.
Conventional Cable	• Standard terminations and joints from local supplier • Easy to make the termination and joints	

Table 6.4: Summary of system components and requirements comparison

6.6 Operational Procedures and Requirements

Both superconducting cables and conventional cables require commissioning test, as it is the most important operational procedure before cable energisation. However, commissioning tests of superconducting cable require additional considerations due to the cryogenic cooling system.

Before commissioning the superconducting cable, a cryostat leak test should be performed, to ensure that there is no damage in the thermal insulation and vacuum pipe. The superconducting cable must be cooled down in a gradual way, avoiding any thermal shock. Liquid nitrogen pressure and flow rating are controlled and monitored at the nominal values, ensuring gradual cool down. Then the DC sheath test and VLF test required for conventional cable are also required for superconducting cable.

While, only the DC sheath test and VLF test are required for the conventional cables to ensure the there is no damage to the cable sheath and insulation during the cable installation process. Additionally, cooling system tests are also required for superconducting cable before the DC sheath and VLF tests begun.

Table 6.5 gives the summary of the operational procedures and requirements of superconducting cables and conventional cables.

	Operational Procedures and Requirements	Remark
Superconducting Cable	• Requires cryostat leak test, liquid nitrogen pressure check and flow rating check. • Requires DC sheath test and VLF	Superconducting cables require additional commissioning tests for the cryogenic cooling system.
Conventional Cable	• Requires DC sheath test and VLF test only	

Table 6.5: Summary of operational procedures and requirements

6.7 Repair Procedures and Requirements

In general, fault repairs of superconducting cables are very complicated and should be performed by specially trained electrical technicians. Additionally, since the repair of superconducting cables involves both warming up and cooling down procedures, it requires significantly longer durations of repair time. However, as the configuration of conventional cable is very simple and standard, normally trained electrical technicians are able to perform the repair procedures. Furthermore, compared with superconducting cable, the repair time is lower.

Additionally, as the superconducting cable system is very complex, any small mistake could lead to a possible fault. Adding to this, the fault repair procedure of the superconducting cable system varies depending on the situation. If a fault happens to the cryogenic cooler, liquid nitrogen pump or cryogenic heat exchanger, the relevant backup equipment should be able to take over, so that superconducting cable can continue to be in service without any interruption. Other than that, if any other fault happens in the superconducting cable, it should be isolated from the grid and warmed up to the ambient temperature before replacing the faulty part of cable.

Table 6.6 summarises the repair procedures and requirements of superconducting cables and conventional cables.

	Repair Procedures and Requirements	Remarks
Superconducting Cable	• Fault repairs could be required for the cable itself, but also for the cryogenic cooling system and vacuum cryostat. • Specially trained electrical technicians are required to perform the repair procedures • Requires long repair time.	The repair procedure and requirements of superconducting cable are much more complex than the conventional cable, and may require longer repair time.
Conventional Cable	• The vast majority of repair requirements are only for the cable itself. • Normal trained electrical technicians to perform the repair • Requires relatively short repair duration time	

Table 6.6: Summary of repair procedures and requirements

6.8 Lifetime Assessment

The lifetime of superconducting cables is expected to be more than 40 years, which is similar to the conventional cables. As long as the superconductor is maintained at the nominal cryogenic temperature, there is almost no degradation. The major reason that could cause the superconductor to be degraded is thermal-cycling. However, up to 200 thermal-cycles, there is no degradation on superconductor, as reported so far [16]. Table 6.7 gives the summary of the lifetime assessment of the superconducting cables and conventional cables.

	Lifetime Assessment	Remarks
Superconducting cable	Over 40 years	The lifetime of the superconducting cable is comparable to the conventional cable.
Conventional cable	Over 40 years	

Table 6.7: Summary of lifetime assessment

6.9 Health and Safety Considerations

The health and safety considerations of conventional cables can be extended to the superconducting cables as well. In other words, all the common health and safety considerations for conventional cables are also applicable to superconducting cable, Damaged cables, for example, could cause a life threat to the people by electric shock, electrical arcs (causing an explosion), and flames, whether they are conventional or superconducting cables.

However, additional safety considerations exist for superconducting cables, due to the requirements of the cryogenic cooling system. These include considerations for liquid nitrogen usage in superconducting cable systems.

Table 6.8 gives the summary of the health and safety considerations of the superconducting cables and conventional cables.

	Health and Safety Consideration	Remarks
Superconducting Cable	• Usage of liquid nitrogen likely causes health and safety issues • Electrical shock due to damaged cable	More health and safety considerations are needed for superconducting cable systems.
Conventional Cable	• Electrical shock due to damaged cable	

Table 6.8: Summary of health and safety consideration

6.10 Capital and Operational Costs

This subsection aims to provide a comparison of the capital and operational costs of superconducting cables with the associated costs of conventional cables.

6.10.1 Cost Comparison - One-to-One

Table 6.9 shows a one-to-one capital cost comparison between superconducting cables and conventional cables of the same ratings. The cost estimates of conventional cables were calculated by data provided by WPD, while the cost estimates of superconducting cables are based on the superconducting cable manufacturers' experience, detailed as below:

- The superconducting tapes contribute to 30 % of the total capital cost, based on the current rating and length of the cable.
- The cryogenic cooling system, including cryostat, termination, joints and cryocooler, contributes to 30-35 % of total capital cost based on the cable voltage rating.
- The remaining 35%-40% is contributed by all other costs, including auxiliary and control equipment.

The ratings of superconducting cables were selected in such a way, so as to provide a direct comparison with conventional cables used by WPD. The specifications of these cables are used to provide the cost comparison between the conventional cables and the relevant superconducting cables as shown in Table 6.9.

Cable Type	Cost of Superconducting Cable (m£)	Cost of Conventional Cable (£)
33 kV/475 A/ 1 km	3.35～4.90	41,129
33 kV/620 A/ 1 km	4.30～6.29	61,949
33 kV/705 A/ 1 km	4.86～7.10	72,727
33 kV/905 A/ 1 km	6.17～9.02	113,956
11 kV/380 A/ 1 km	2.64～3.90	15,358
11 kV/495 A/ 1 km	3.37～4.97	19,409
11 kV/635 A/ 1 km	4.26～6.29	52,615
11 kV/720 A/ 1 km	4.80～7.08	65,465
11 kV/905 A/ 1 km	5.97～8.82	98,231

Table 6.9: Cost comparison between superconducting and conventional cables

As shown in Table 4.1, the cost of a superconducting cable can be 100 times larger than the cost of a conventional cable of the same rating. Therefore, it is clear that replacing a conventional cable with just a superconducting cable of the same specifications is not realistic. Or, in other words, where a single conventional cable can be used to carry the required amount of power, superconducting cables should not be considered as an alternative due to their high costs.

6.10.2 Cost Comparison - One Superconducting Cable Vs Multiple Conventional Cables (Same voltage level)

As explained in Chapter 2, the challenge of using conventional cables arises whenever bulk power needs to be transmitted over a long distance, limiting the length of the cables due to the large voltage drop and high power losses. A number of conventional cables could also be required to carry all the power that needs to be transferred. These cases would result in considerably high space and land requirements, as a number of cables would need to be installed. This is incredibly challenging at urban locations where underground space is limited and expensive.

Superconducting cables, however, have much larger power density than conventional cables, meaning that a single superconducting cable could be used to transfer huge amounts of power that would otherwise require a number of conventional cables. Hence, the next stage of the cost investigation looks at the case of a single superconducting cable, replacing multiple conventional cables.

Type	Quantity	Voltage (kV)	Current (A)	Capacity (MVA)	Cost (£/km)	Ratio (Superconducting/ Conventional)
Conventional Cable	1	33	905	52	113,956	54.14
Superconducting Cable	1	33	905	52	6,170,000	
Conventional Cable	2	33	905	104	227,912	52.87
Superconducting Cable	1	33	1800	104	12,050,000	
Conventional Cable	3	33	905	156	341,868	52.51
Superconducting Cable	1	33	2700	156	17,950,000	

Table 6.10: Cost comparison of one 33 kV superconducting cable replacing of multiple 33 kV conventional cables

Type	Quantity	voltage (kV)	Current (A)	Capacity (MVA)	Cost (£/km)	Ratio (Superconducting /Conventional)
Conventional Cable	1	11	905	17	98,231	58.94
Superconducting Cable	1	11	905	17	5,790,000	
Conventional Cable	2	11	905	34	196,462	59.35
Superconducting Cable	1	11	1800	34	11,660,000	
Conventional Cable	3	11	905	51	294,693	58.94
Superconducting Cable	1	11	2700	51	17,370,000	

Table 6.11: Cost comparison of one 11 kV superconducting cable replacing of multiple 11 kV conventional cables

Table 6.10 and Table 6.11 show the cost comparison of one superconducting cable replacing multiple conventional cables, while maintaining the same amount of power being transferred. The cost of the superconducting cable I found to be around 60 times more than the cost of the relevant multiple conventional cables.

However, multiple conventional cables require large dimensions of the right of way, and also result in much more civil work costs compared with a single superconducting cable. Considering these factors, the cost difference between the superconducting cables and conventional cables can be further reduced, but the difference is still expected to remain significant.

6.10.3 Cost Comparison - 1 Superconducting Cable Vs Multiple Conventional Cables (Different Voltage Level)

Superconducting cables have very low losses compared to conventional cables, irrespective of the operating voltage. This makes it feasible to use a superconducting cable operated at much lower voltage than the conventional cable, with a significant reduction in losses. Table 6.12 provides the cost comparison of multiple 33 kV conventional cables being replaced by a single 11 kV superconducting cable.

11 kV and 33 kV cables have very similar capital costs, therefore replacing multiple 33 kV conventional cables with a single 11 kV superconducting cable doesn't make it cost effective, but gives a higher cost ratio than replacing them with superconducting cables of the same voltage rating as shown in Table 6.10 and Table 6.11. This proves that such an implementation should not be considered.

Type	Quantity	Voltage (kV)	Current (A)	Capacity (MVA)	Cost (£/km)	Ratio (Superconducting /Conventional)
Conventional Cable	1	33	905	52	113,956	152.43
Superconducting Cable	1	11	2700	52	17,370,000	
Conventional Cable	2	33	905	104	227,912	154.23
Superconducting Cable	1	11	5500	104	35,150,000	
Conventional Cable	3	33	905	156	341,868	152.95
Superconducting Cable	1	11	8200	156	52,290,000	

Table 6.12: Cost comparison of one 11 kV superconducting cable replacing multiple 33 kV conventional cables

Therefore, the next step in this study involves the comparison of 132 kV conventional cables with superconducting cables of lower voltage rating, as the cost of 132 kV conventional cables is significantly higher than 33kV and 11kV cables.

Table 6.13 gives the cost comparison of one 11 kV or 33 kV superconducting cable replacing one 132 kV conventional cable of the same amount of capacity. It is observed that the superconducting/conventional cost ratio has been significantly reduced, meaning that using superconducting cables to carry 132kV load is a case that should be investigated further.

Type	Quantity	Voltage (kV)	Current (A)	Capacity (MVA)	Cost (£/km)	Ratio (Superconducting /Conventional)
Conventional Cable	1	132	166	38	1,000,000	4.97
Superconducting Cable	1	11	2000	38	4,965,000	
Conventional Cable	1	132	500	114	1,000,000	6.15
Superconducting Cable	1	33	2000	114	6,150,000	

Table 6.13: Cost comparison of one 11 kV and 33 kV superconducting cable replacing of multiple 132 kV conventional cables

Although the cost ratio is still high, indicating that superconducting cables are significantly more expensive than conventional cables, other factors need to be considered, before making any recommendations. These include savings in civil works, right-of-way and land costs, removing the necessity of additional substations, high voltage equipment etc.

For this reason, a specific case study will be performed in Work Package 2, considering a real network example where a substation has been traditionally reinforced and comparing with the proposed superconducting cable implementation. From this cost analysis, it is clear that this case study should consider a superconducting cable implementation at either a 132/11kV or 132/33kV site.

Chapter 7

Summary, Key Outputs and Next Steps

7.1 Summary of Work Package 1

This report presents the work completed as part of Work Package 1, of the Superconducting Cables network feasibility study.

The document started with an overview of the problem that we are trying to solve, highlighting the importance of finding new ways of adding extra capacity to our electricity distribution networks and explaining the motivation behind this work.

In Chapter 3, an overview of the history and development of superconducting cable technologies, including previous worldwide demonstration projects has been provided to give an understanding of the technology background.

Chapter 4 included the investigation of the key aspects of Superconducting Cable implementations, providing sufficient knowledge to understand the structure of such systems and their main challenges.

In Chapter 5, the same aspects have been explored for the conventional cables currently used by most UK Distribution Network Operators.

The information presented in Chapters 4 and 5 has then been used to perform the comparisons on each key aspect of superconducting and conventional cables, forming the Cost Benefit Analysis of Chapter 6.

7.2 Key Outputs and Next Steps

Electricity distribution networks, especially in urban locations, are rapidly reaching their capacity limits requiring reinforcement. At such locations, land and space availability could prevent the implementation of traditional reinforcement methods like building new substations or installing additional transformers. Therefore, investigating alternative approaches to provide extra network capacity is incredibly important.

Interconnecting substations to transfer spare network capacity to the point in the network where it is needed is one way of reducing the need for additional land (new substations) or space (additional equipment). Conventional cables can be used to achieve this, however, their high losses and large voltage drop means that they are limited to the distance they can be used for. Furthermore, the limited capacity of conventional cables means that a number of cables would be required for bulk power transfers, requiring significant civil works, right-of-way and underground space. The unique characteristics of superconducting cables including their high power density, low losses and reduced space requirements, could enable the interconnection of substations, hence overcoming the challenges of conventional cables.

Therefore, each of their key aspects has been investigated and compared to conventional cables to form a detailed Cost Benefit Analysis. This CBA is summarised in Table 7.1:

Superconducting Cables Benefits	Superconducting Cables Limitations	Conventional Cables Benefits	Conventional Cables Limitations
Compact cable configurations.	Specially designed cable terminations and joints. and additional cooling system required.	Simple cable configuration.	Limited power carrying capacity.
High current density, smaller cable size, low losses, no thermal and electromagnetic impact, requires small right-of-way.	Special operational and repair procedures for cooling system.	Standard cable terminations and joints.	Bigger size.
Similar installation procedures with conventional cables.	Additional repair procedures required for cryogenic cooling system.	Standard and simple installation.	Limited distance over which they can be used.
Comparable lifetime with conventional cable.	Additional health and safety considerations are required due to the usage of liquid nitrogen.	Potentially less repair time.	High losses and voltage drop.
	Additional operational costs due to the consumption of liquid nitrogen and electricity for cryogenic cooling system.	Lower capital and maintenance costs.	

Table 7.1 - CBA Summary

The unique benefits of superconducting cables could be exploited to solve challenging capacity problems in urban electricity distribution networks.

From the CBA, it is clear that the main drawbacks of superconducting cables arise from the fact that DNOs don't have experience with such systems, requiring specialised staff to assist with their operational and maintenance procedures. This, however, is a challenge that can be overcome by DNOs, as experience and skills can be gained through an implementation project.

Through this investigation, it has been shown that the costs of such systems can be significant. However, the previous and future worldwide demonstration projects show that the interest in the area keeps increasing as costs reduce over the years. For this reason, a detailed costs investigation was performed as part of the CBA, to identify where in the network it would be more beneficial to consider such an implementation. This has shown that the cost difference between superconducting cables and conventional cables reduces significantly when considering the 132kV level. Such an implementation would offer additional savings as the conventional solution would not only involve the installation of 132kV cables but also 132kV/11kV or 132kV/33kV transformers, or even building completely new substations to provide the required additional capacity.

Therefore, an investigation of a superconducting cable implementation to add capacity at a 132/11kV or 132/33kV substation is recommended.

For this reason, the following work package of this Network Feasibility Study will consider a previous reinforcement project of a 132/11kV or 132/33kV substation implemented with one of the conventional approaches. The transfer of available network capacity from a nearby substation using superconducting cables will then be investigated for that particular case to enable comparisons to be made between the two implementations.

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