

**NEXT GENERATION
NETWORKS**

**SUPERCONDUCTING CABLES
NETWORK FEASIBILITY STUDY**

WORK PACKAGE 2



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Glossary

Abbreviations	Terms
DNO	Distribution Network Operator
HTS	High Temperature Superconductors
SC	Superconducting Cable
XLPE	Cross-linked Polyethylene
PV	Present Value
FV	Future Value
CBA	Cost Benefit Analysis
GSP	Grid Supply Point

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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, and 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 Findings from Work Package 1

Work Package 1 aimed to explore the existing superconducting cable technologies and compare them with the conventional cable solutions. It presented the history of the superconducting cable technology and previous implementation projects in electricity distribution networks. Furthermore, in order to understand the structure of superconducting cable systems and their main challenges, their key aspects were analysed, including the installation, operational and repair procedures and requirements, maintenance requirements, expected lifetime and costs. The same aspects were discussed for the conventional cables, finally forming a Cost Benefit Analysis comparing the two technologies.

Through the investigation of Work Package 1, it has been shown that superconducting cables have unique benefits which could help solve challenging capacity issues in electricity distribution networks. The main output from the costs analysis was that the costs of such systems can be significant but the cost difference between superconducting cable system

and conventional solutions decreases significantly when considering work required on the 132kV level. This is because traditional reinforcement at that level is the most expensive.

Therefore, it was concluded from Work Package 1, that in the following work of this network feasibility study, a previous reinforcement project of a 132/11kV or 132/33kV substation implemented with one of the conventional approaches should be considered for a more detailed CBA between the two technologies to be performed.

1.5 Introduction to Work Package 2

This report presents the findings from Work Package 2 of this Network Feasibility Study.

Since Work Package 1 indicated that a previous reinforcement project at a 132kV/11kV or 132kV/33kV substation should be considered in the case study, the work commenced with the selection of such a project. This is presented in Chapter 2. To help the reader understand the problem that needs to be solved and the options available, Chapter 3 presents the conventional and superconducting solutions to the capacity problem of the chosen case. To further explore the impact of each solution in the electricity network, a number of power system studies have been completed in PSCAD which provided valuable learning on the electrical losses each solution produces, the expected power flows from each and the impact on the network fault levels. Chapter 4 then uses all the learning presented in the previous Chapters to perform the Cost Benefit Analysis. This CBA provides a straightforward way to compare the two solutions and process all the information collected. Chapter 6 explores the future of the superconducting cables and finally, Chapter 7, summarises the conclusions of this Work Package and presents the next steps in this network feasibility study.

Chapter 2

Site selection

This chapter forms an important part of this report, as it describes the criteria used for selecting the most promising site among the available cases. These criteria are evolved from the measures proposed by the industry in addition to the findings from Work Package 1 report. Thus, the chosen specific case would form the basis of the investigation and enable us to understand the limitations and specific applications where the superconducting cable will be feasible in terms of both cost and efficiency.

Work Package 1 has shown that a capacity related reinforcement project at a 132/11kV or 132/33kV substation should be considered since the cost of traditional reinforcement at such voltage levels is high and would have the smallest cost difference with the superconducting cable solution. Projects that involve building a new substation would be a good candidate for this case study, since they involve the highest costs. For this reason, the focus was on identifying such projects.

Finding a previous project that fit all the said criteria was challenging, therefore the project that was closest to what was required was chosen. The aim, was to see whether building a new substation to meet an increase in capacity, could be avoided by implementing a superconducting cable solution instead.

The criteria used when selecting the specific site are:

- Proximity to the urban location
- Land scarcity and high real estate price
- Replacement of HV cables with LV cables
- Power capacity to be transferred and
- Cable layout path

Based on the above criteria, a simple case by case approach had been established which led to the selection of the specific site requiring reinforcement. This specific case is named as Substation-A for demonstration purposes and will be explored further in the following subsections.

2.1 Overview of the chosen case

Site A is the chosen substation site which was requiring reinforcement due to capacity issues.



Figure 2.1: The location of Substation-A

Site A is a 33/11kV substation with 2 x 12/24 MVA 33/11 kV transformers fed from 2 x 132/33 kV 60 MVA transformers at the same site. The 132/33kV transformers were supplied by Substation-C GSP via two 132 kV circuits.

There were two main issues in the network, which created the need for the reinforcement works. The first was that the 33/11 kV transformers at site A were approaching their firm capacity. The second was that Substation-C GSP which was supplying Substation-A was close to not being compliant under second circuit outage conditions in the winter. This is demonstrated in Figure 2.2.

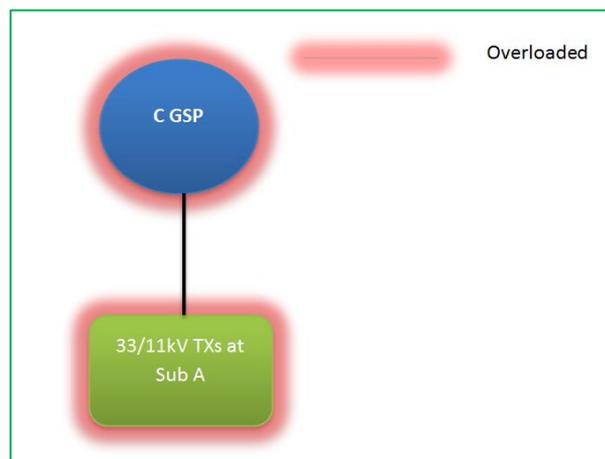


Figure 2.2: Capacity issues at chosen site

Therefore, it was decided that certain reinforcement works were necessary at Site A.

The conventional solution involves installation of additional 132/11 kV transformers on site, to increase the power capacity. This requires both 132 and 11 kV power equipment, such as

busbars, power cables and switchgear, additional 132kV infeed's supplied from the nearby 132kV network and civil works to build the new switch rooms and required structures.

Alternatively, based on the recommendations from Work Package 1, 11kV superconducting cables could be used to transfer the required capacity from a nearby site. To comply with Engineering Recommendation P2/6¹ two infeed's will be required to provide the capacity, something that could be implemented either using two superconducting cables or one superconducting cable and one 132kV infeed feeding one 132/11kV transformer. The challenges involved in designing the superconducting cable solution, including the identification of the appropriate nearby Substation and the most suitable cable layout route are demonstrated in the following Chapter Once the superconducting cable implementation route is decided, it will be used to further investigate in the business case study.

¹ Energy Networks Association, Engineering Recommendation P2/6 – Security

Chapter 3

Solutions considered for the Reinforcement

In this chapter, the two solutions to the capacity problem of the selected site are presented. The conventional solution involves establishing a new 132/11kV site with two 132/11kV 39 MVA transformers at Substation-A, while the superconducting solution removes the need for two transformers by providing the second infeed using an 11kV superconducting cable transferring the available capacity from a nearby site.

3.1 Conventional solution

The conventional solution for this reinforcement project requires two 132kV power cables to provide the two infeed's to the new 132/11kV site. In the current case, as the Grid Supply Point (GSP) that was originally feeding Substation-A was also reaching its firm capacity, the new 132kV infeed's would be provided from a different GSP.

Figure 3.1 gives the single line diagram of Substation-A before reinforcement. And Figure 3.2 gives the single line diagram of Substation-A after reinforcement, based on the proposed conventional solution. In this conventional solution, it was decided to replace the two 33/11kV 24MVA transformers with two 132/11kV 39MVA transformers in the Substation-A, and feed them from Substation-E GSP instead of Substation-C GSP, by installing two new 132kV circuits. This solution removes some load from Substation-C GSP to ensure it is compliant under N-2 conditions but also provides more capacity at Substation-A. Table 3.1 describes the works that are involved in the conventional reinforcement solution and the estimated cost is about £13.5 million, which will be analyzed in detail, in Chapter 5.

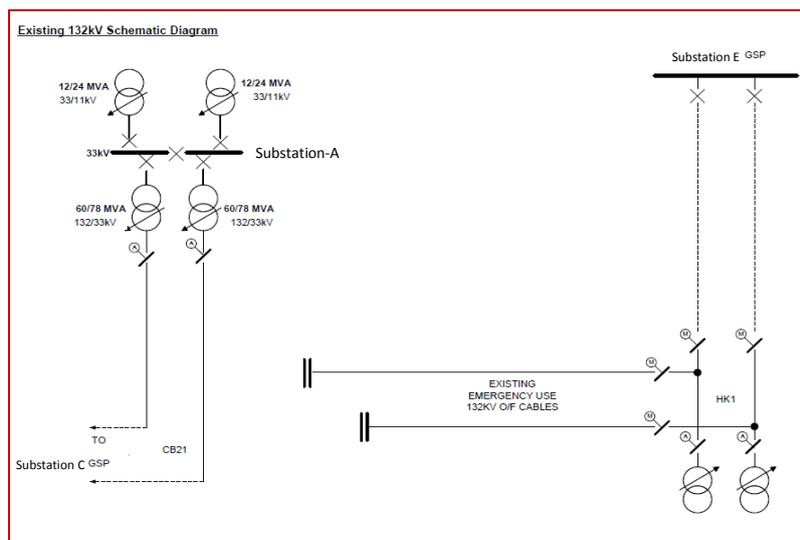


Figure 3.1: Substation-A before reinforcement

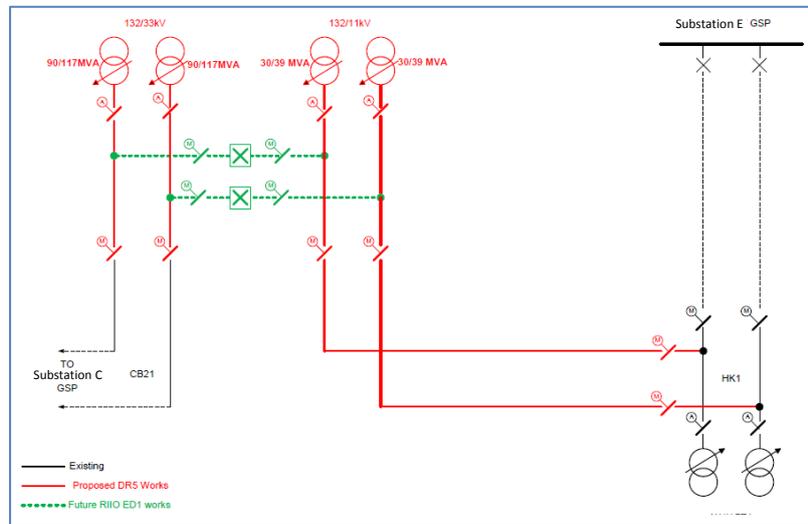


Figure 3.2: Substation-A after reinforcement

The work involved in carrying out this conventional reinforcement solution has been detailed in Table 3.1. As observed from Figures 3.1 and 3.2, the reinforcement work requires replacing the existing 33/11 kV, 24 MVA transformers with transformers of higher power rating i.e. 39 MVA. The 132kV cables make a big proportion of the overall cost and work, while all the remaining auxiliary equipment is common in both solutions. The main parameters of the 132 kV XLPE cable for Substation-A reinforcement are listed as in Table 3.2.

Table 3.1: Work involved with the conventional solution

Work for conventional solution	
1	Replacement of 33/11 kV 24 MVA transformers with 132/11 kV 39MVA transformers
2	Installation of 12 new 132 kV isolators and associated structures at Substation-A
3	Change the network connectivity to transfer the 132/11 kV transformers onto the new 132kV circuits fed from Substation-E rather than Substation-C
4	Connect 132 kV circuits into Substation-D via new line isolators
5	Layout site at Substation-A for future 132 kV circuit breaker for interconnection between Substation-E GSP and Substation-C GSP

Table 3.2: The specifications of the 132 KV XLPE cable

Items	Values
Rated voltage (kV)	132
Operating temperature of conductor (°C)	90
Rated capacity (MVA)	40
Current carrying capacity (A)	180
Length of cable (km)	5.75

3.2 The superconducting cable solution

Instead of building a completely new substation, an alternative solution is to interconnect the 11kV sides of the substations using an 11kV superconducting cable. Considering its high power density, a single superconducting cable all alone is capable enough to transfer the additional power required from one of the neighboring 132/11 kV substations, where spare capacity is readily available. According to Engineering Recommendation P2/6, a second infeed using the conventional high voltage cable is required. Thus, a 132 kV cable in series with a 132/11 kV transformer will be providing the second infeed to the site, meeting the n-1 security of supply requirements. Figure 3.3 shows Substation-A and its neighbouring substations, which, for the purposes of this study, are assumed to have spare capacity available.

As already mentioned in the WP1 report, there are a limited number of restrictions for the superconducting cable installation. Considering these limitations i.e. route selection and the site layout, the design of the superconducting solution is discussed in the following subsections.

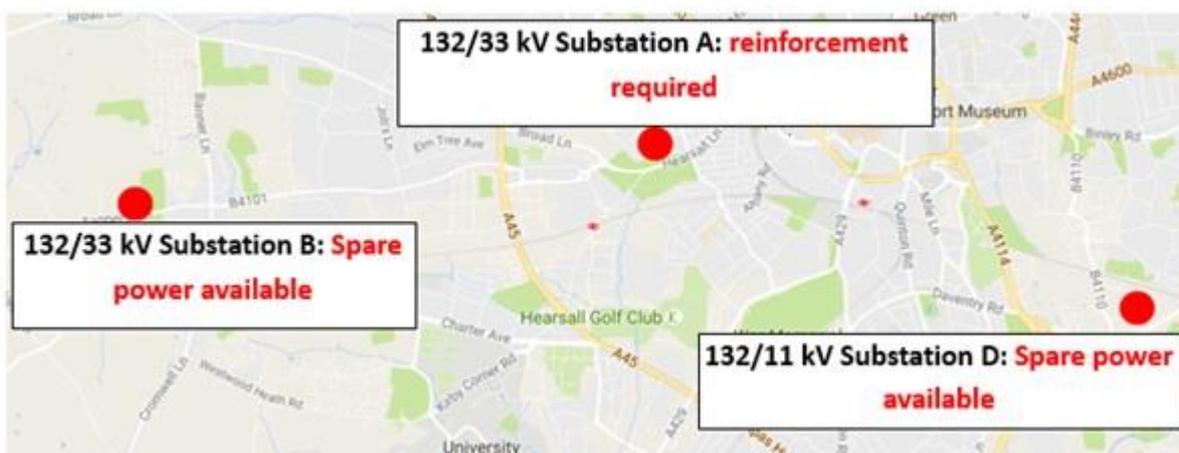


Figure 3.3: Substation-A and its neighboring substations

3.2.1 Superconducting Cable Route Selection

In order to choose a possible route for the superconducting cable installation, the following criteria are considered:

- i. It is preferable to follow an existing available underground cable route for installing one additional superconducting cable, (i.e., existing route).
- ii. The length of the cable route should be minimal, (i.e., shortest length).
- iii. It is preferable to avoid sharp bends and bumps, the whole route for superconducting cable should be as flat as possible, (i.e., with a large radius of curvature).

Based on the selection criteria, one of the two neighboring substations will be selected to provide additional power to the Substation-A and one route will be selected for the installation of the superconducting cable. In order to minimize the investment of superconducting cable installation as much as possible, the priority level applies to the selection criteria:

- i. The shortest route is the first priority to reduce the overall investment.
- ii. The existing route is the second priority to reduce the civil investment.
- iii. The flat route is the third priority to simplify the cable installation.

Figure 3.4 demonstrates the priority level of the selection criteria.

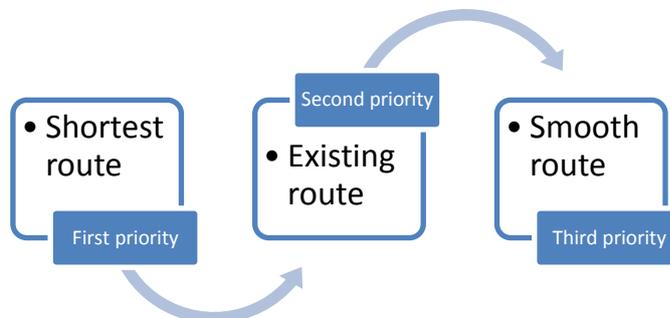


Figure 3.4: The priority level of selection criterions

3.2.1.1 Substation-D to Substation-A

Between the Substation-D and Substation-A, there is one possible underground cable route for superconducting cable installation, which is shown in Figure 3.5 (route ID: W-C). The total length of the route is about 5 km. This underground cable route is mainly across the densely populated residential area.

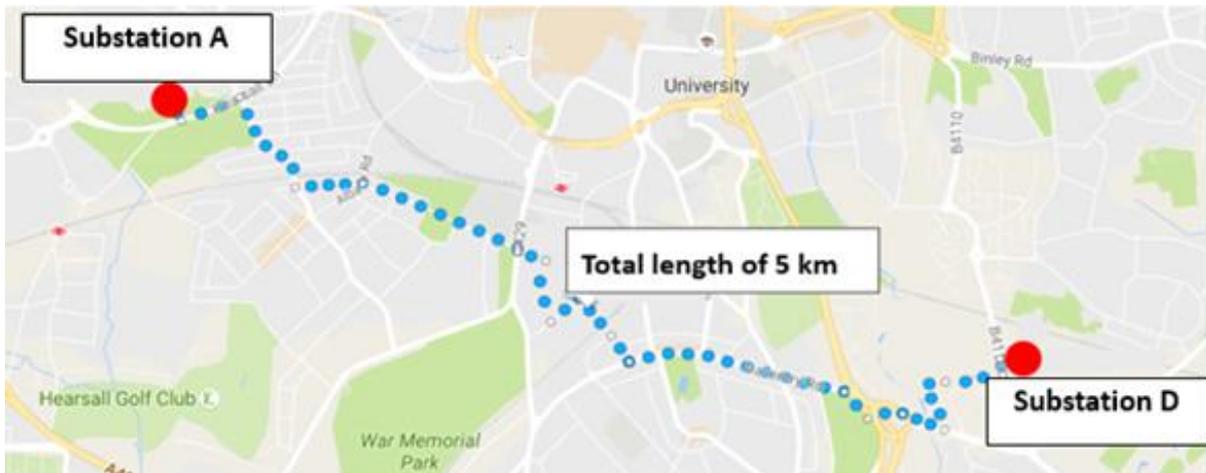


Figure 3.5: Possible superconducting cable route between Substation-A and Substation-D (route ID: W-C)

3.2.1.2 Substation-B to Substation-A

There is one possible underground cable route for the superconducting cable installation between Substation-B and Substation-A, with a total length of about 5.0 km. The route ID is C-C. This existing underground cable route is mainly across a residential area, as shown in Figure 3.6.



Figure 3.6: Possible superconducting cable route between Substation-B and Substation-A (route ID: C-C)

Table 3.3 summarizes all the possible routes for superconducting cable implementation. Substation-E GSP provides the power to the Substation-D and Substation-C GSP provides the power to Substation-B substation. Originally, all of the power to Substation-A is provided by Substation-C GSP. However, with the maximum power demand of Substation-A increased to 40 MVA (originally 24 MVA), is the Substation-C GSP originally feeding Substation-A will no longer be compliant with the minimum supply capacity requirement for second circuit outage condition. Hence, Substation-A should be fed from another GSP. For this reason, Substation-D is chosen to provide additional power to Substation-A.

Table 3.3: The summary of possible superconducting cable implementation route

Substations	Route ID	Length (km)	Smooth level	Power source
Substation-D	C-W	5.0	smooth	Substation-C GSP
Substation-B	C-C	5.0	Very smooth	Substation-E GSP

3.2.2 Structure of the Superconducting Cable infeed

Superconducting cables should operate at around 70K, hence a cooling system is in place to ensure the required operating temperature. A typical superconducting cable system contains:

- a. The superconducting cable body
- b. The cable termination and joints
- c. The cooling system

Normally, the length of one piece of superconducting cable is around 500 meters, mainly limited by the manufacturing technique. Hence, for superconducting cable in the range of kilometers, cable joints should be installed every 500 meters. At each end of the superconducting cable, there is a cable termination similar with the conventional underground cable. But the cable termination for superconducting cable has a unique function: superconducting cable termination is the interface between the conventional power grid at room temperature and a superconducting cable at cryogenic temperature. A cooling system is the main cooling source for the entire length of the superconducting cable. Depending on the total length of the cable, the cooling system usually connects one or both cable terminations to provide circulating sub-cooled LN₂ to the superconducting cable. These fundamental characteristics of the superconducting cable system provide a guideline for the design of the 11 kV superconducting cable solution of this case study, with the final design demonstrated in Figure 3.7.

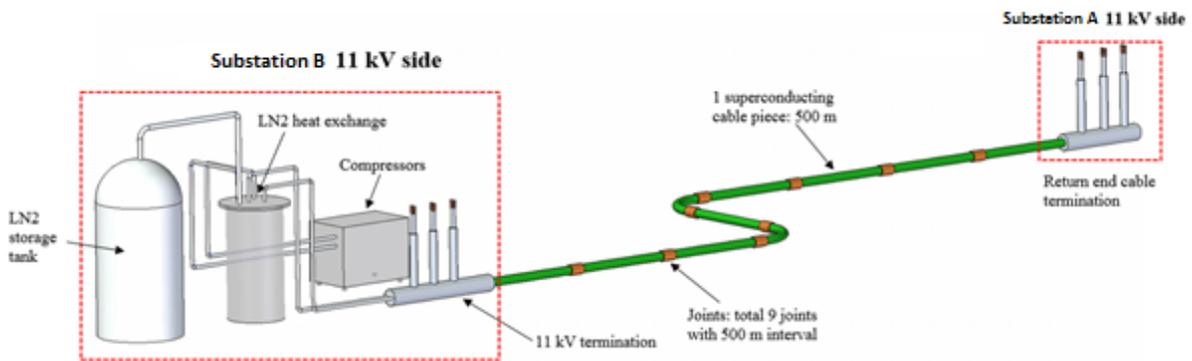


Figure 3.7: The layout of the completed superconducting cable system for Substation-A reinforcement

3.2.3 Configuration and Specification details

From the learning gained from Work Package 1, there are three superconducting cable configurations. The determination of each configuration is mainly based on the voltage level and Table 3.4 gives a summary. The detailed study of each superconducting cable configuration has been completed in Work Package 1 of this project [1], which indicated that at 11kV, the superconducting cable configuration should be triaxial. The configuration of 11 kV triaxial superconducting cable is shown in Figure 3.8.

Table 3.4: The three configurations of superconducting cable

Configuration	Voltage level
Triaxial	< 33 kV
Triad or Three in one	33-66 kV
Three separated phase	Over 110 kV

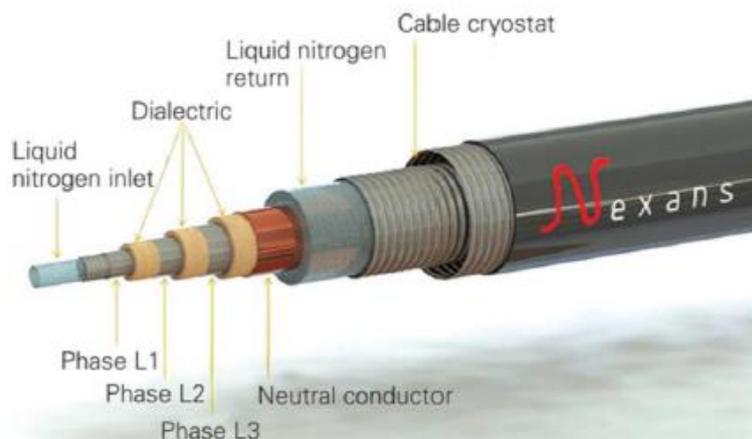


Figure 3.8: The configuration of 11 kV triaxial superconducting cable

The triaxial cable design will contribute to a cost reduction, as the majority of the cable price is determined by the volume of superconducting material used which is minimised in this configuration. Following this design, the main parameters of 11 kV superconducting cable for Substation-A reinforcement are listed in Table 3.5.

Table 3.5: The specifications of 11 kV superconducting cable

Items	Values
Rated voltage (kV)	11
Operating temperature of conductor (°C)	70
Rated capacity (MVA)	40
Current carrying capacity (A)	2100
Length of cable (km)	5

Chapter 4

Modelling

4.1 Introduction

To further explore the impact of each solution in the electricity network, a number of power system studies have been done in PSCAD, which provided valuable learning on the electrical losses each solution produces, the expected power flows from each and the impact on the network fault levels. This Chapter describes the power system studies performed and discusses the results.

The three main aims of this simulation study are:

- i. Understand the impact of each solution on the network's power flows: This is important for planning the future expansion of the distribution network, as the new transmission cable installed into the existing distribution network will cause significant changes in the power flow.
- ii. Understand the impact of each solution on the short circuit current level: In the case of faulty conditions, it is important to determine the fault current level and its duration, to prevent the catastrophic damage to the distribution network.
- iii. Understand the impact of each solution on the resistive losses: Reducing transmission line losses for efficiency improvement is very important for network operators. Hence, it is of interest to estimate the total losses and power savings by using superconducting cables in the distribution network.

4.2 The background of the case study and simulation methodology

Both the conventional solution and superconducting cable solutions will be considered for the reinforcement, exploring the aspects of their performance, operation and cost. The results of the simulation will provide information on the impact of each solution on the network power flows, fault current level and resistive losses.

It is important to understand that the operation of the network could be affected by the use of superconducting cables due to their very low impedance, which may cause a number of uncertainties. These include:

- i. Compared with underground copper cables, the impedance of superconducting cable is much lower. When installing the superconducting cable into the networks consisting of conventional circuits with higher impedances, the superconducting cable will naturally attract power flow. Thus the magnitude and the direction of the power flow in the network may be changed.
- ii. Also due to the very low impedance of superconducting cables, the fault current level may be several times higher than the equivalent conventional circuits, which requires implementation of protection systems.

Therefore, by knowing the impact of the superconducting cable on the network, DNOs would be able to handle the above uncertainties. Table 4.1 summarizes the areas examined in the simulations.

Table 4.1: The brief summary of the simulation study

Objectives	Descriptions
Power flows	Examine the change of power flow in the entire simulated network when the superconducting cable is installed
Fault current levels	Examine the increased level of fault current when the superconducting cable is installed in the network
Resistive losses	Examine the resistive losses that can be saved by superconducting cable over the entire lifetime, compared with the conventional solution

4.3 The methodology of the network simulation using PSCAD/EMTDC

The simulations have been performed using the standard power system software PSCAD/EMTDC. PSCAD (Power System Computer Aided Design) is a graphical user interface while EMTDC (Electromagnetic Transients including DC) is a program estimating electromagnetic transients. The graphics-based models can be compiled into the Fortran language, computed in the EMTDC and the results can then be transferred back to PSCAD to display.

4.3.1 Overview of the simulated circuit for conventional solution

The conventional solution to the capacity problem at Substation-A, involves providing the 40 MVA capacity by replacing the two 33/11kV 24MVA transformers with two 132/11kV 39MVA transformers and feeding them from a different GSP than the one originally feeding Substation-A.

Figure 4.1 shows the overall electrical circuit diagram for Substation-A reinforcement based on the conventional solution. Two new 132 kV distribution lines are constructed and transfer power from Bus 2 in Substation-D to Buses 8 & 10 in Substation-A, providing the infeed to the 132/11 kV transformers.

Each transmission line is connected to a power meter to indicate the magnitude and direction of the active and reactive power flowing. Bus 1 is used to emulate the 275 kV national grid transmission line with the constant voltage source connected. Hence, Bus 1 is used as the slack bus in the power flow study.

For determining the fault level, a phase (A) to ground (G) fault is applied to the new distribution lines from Bus 2 to Bus 2 & 10 as shown in Figure 4.1. The duration of the fault is set as 0.06s. When the fault is applied, the Phase A will have zero resistance to the ground.

The parameters of the transformers and distribution lines are listed in Table 4.2 and 4.3 respectively. These parameters have been extracted from WPD’s planning tool.

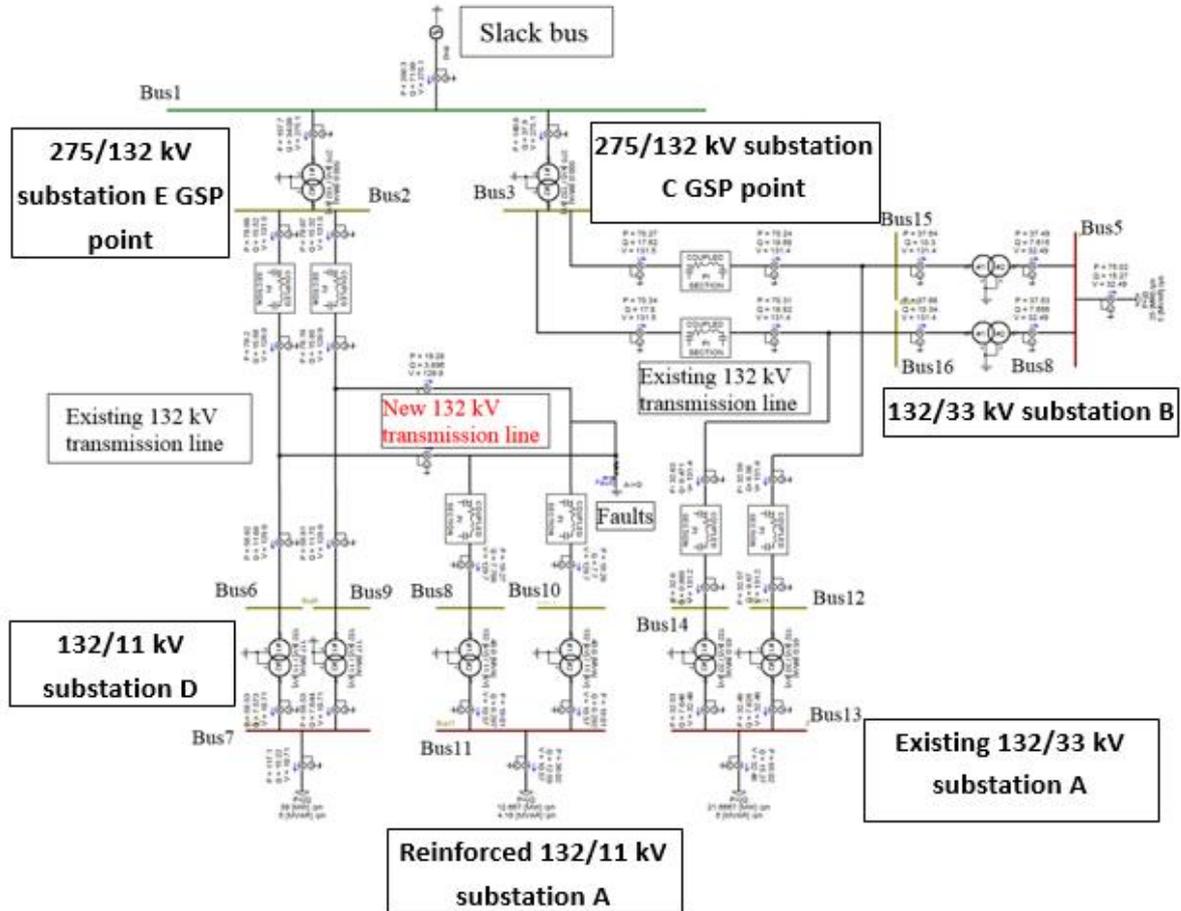


Figure 4.1: The overall simulation circuit diagram for conventional solution

Table 4.2: The parameters of transformers

No.	Location	From Bus	To Bus	Copper losses (p.u.)	Eddy current losses (p.u.)
1	Substation-D 1 (132/11 kV)	6	7	0.01156	0.00021
2	Substation-D 2 (132/11 kV)	9	7	0.01147	0.00021
3	Substation-B 1 (132/33 kV)	15	5	0.00707	0.00021
4	Substation-B 2 (132/33 kV)	16	5	0.00703	0.00021
5	Substation-A 1 (132/11 kV)	8	11	0.02241	0.00021
6	Substation-A 2 (132/11 kV)	10	11	0.02241	0.00021
7	Substation-A 1 (132/33 kV)	12	13	0.00394	0.00021
8	Substation-A 2 (132/33 kV)	14	13	0.00394	0.00021

Table 4.3: The parameters of distribution lines

No.	Line name	From Bus	To Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	Substation-D to Substation-A 1	2	8	0.001722	0.003015	0.099132
2	Substation-D to Substation-A 2	2	10	0.001722	0.003015	0.099132
3	Substation-E to Substation-D 1	2	6	0.012188	0.027259	0.01387
4	Substation-E to Substation-D 2	2	9	0.012228	0.027267	0.016193
5	Substation-B to Substation-A 1	16	12	0.002365	0.00928	0.016446
6	Substation-B to Substation-A 2	15	14	0.002384	0.009314	0.017169
7	Substation-B to Substation-C 1	3	15	0.000616	0.001272	0.011375
8	Substation-B to Substation-C 2	3	16	0.000602	0.00123	0.010962

4.3.2 Overview of the simulated circuit for superconducting solution

Figure 4.2 shows the overall electrical circuit diagram for the Substation-A reinforcement based on the superconducting cable solution. A new 11 kV superconducting cable is constructed and takes 40 MVA power from the Bus 7 in the Substation-D to the Bus 11 in the Substation-E as the direct infeed to the local distribution load.

Each transmission line is connected with circuit breakers (red rectangular) to indicate the magnitude and direction of the active and reactive power flowing. The Bus 1 is used to emulate the 275 kV national grid transmission line with the constant voltage source connected with. Hence, the Bus 1 is used as the slack bus in the power flow study. Similar to the conventional solution, phase A to ground fault is applied to the superconducting cable

line from Bus 7 to Bus 11 as shown in Figure 4.2. The duration of the fault is set as 0.06 s. When the fault is applied, the Phase A will have zero resistance to the ground.

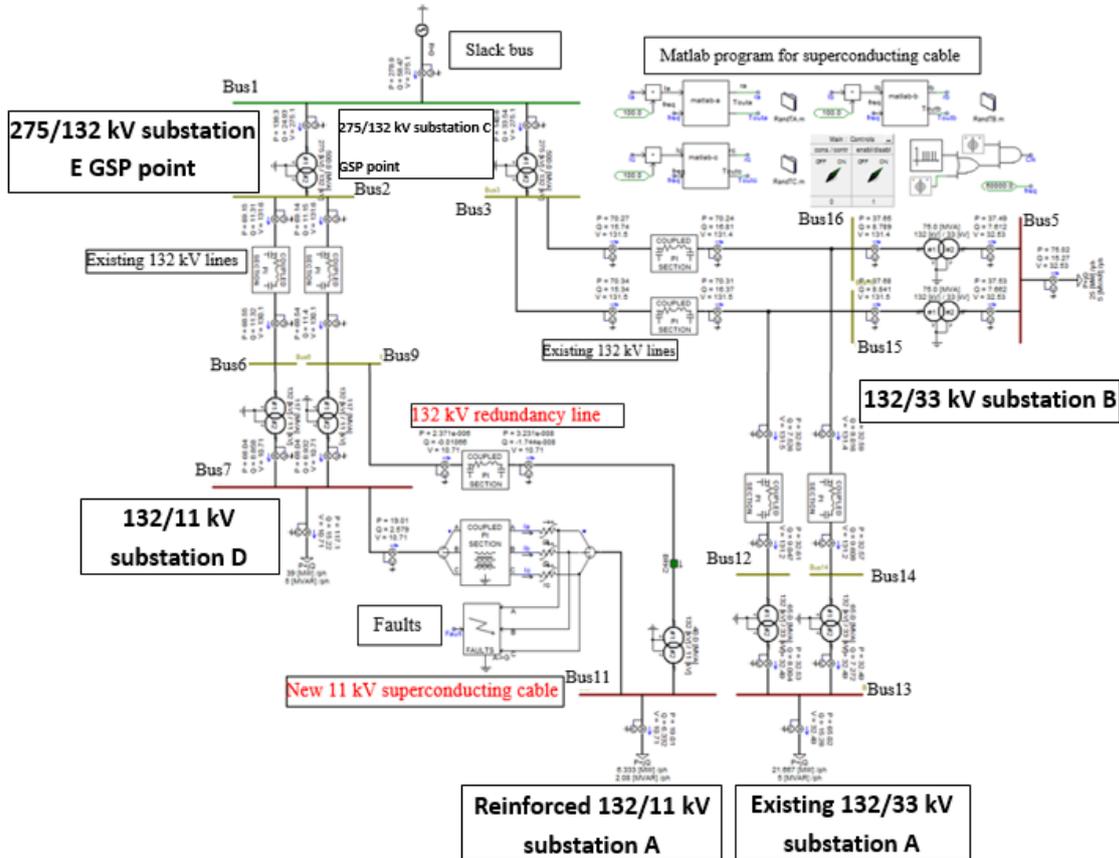


Figure 4.2: The overall simulation circuit diagram for superconducting cable solution

The superconducting cable in the model is programmed based on the parameters in Table 4.4. The current rating of the superconducting cable is 2.3 kA, which is able to provide 40 MVA power with 11 kV distribution voltage. The operating temperature of the cable is designed between 65 and 77 K. The specific operating temperature is based on the design of the cooling system. Lower operating temperature will benefit to improve the cable performance and reduce the bubbles in the dielectric. In this simulation study, the operating temperature is assumed as 70 K initially. The impedance of the superconducting cable is referred to Table 4.5, where the resistance and inductance of the superconducting cable in the steady state can be obtained based on the impedance of the conventional underground cable.

Table 4.4: The parameters of the superconducting cable in the model

Parameters	Values
Voltage rating	11 kV
Current rating	2.3 kA
Power capacity	40 MVA
Length	5 km
Operating temperature	65-77 K

Table 4.5: The comparison of power transmission technology

Technology	Resistance (ohm/km)	Inductance (mH/km)	Capacitance (nF/km)
Superconducting cable	0.0001	0.06	200
Conventional underground cable	0.03	0.36	257
Overhead line	0.08	1.26	8.8

4.4 Modelling Superconducting properties

Unlike the conventional power components, whose resistivity is maintained constant during the fault condition, the characteristic of superconducting resistance is a function of current density and temperature, and a circular dependency arises because the current density calculation contains the resistivity, leading to a resistivity that is dependent on itself. Hence, it is essential to simulate the behavior of the superconducting cable in the power system before using it in power grids. However, there is no existing superconducting component that can be directly used in PSCAD/EMTDC. Hence, the development of a superconducting component in PSCAD/EMTDC is necessary.

4.4.1 Construction of the superconducting tape and its characteristics

In PSCAD/EMTDC, the superconducting component will be developed in such a way that the resistivity of the superconducting tape is a piecewise function of the temperature for each layer of HTS tape, considering the coated structure of the superconducting tape in PSCAD/EMTDC. The typical configuration of superconducting tape, which is used to fabricate a superconducting cable, is shown in Figure 4.3. It shows that the superconducting layer (“HTS” as shown in the figure, HTS stands for the high temperature superconductor) is deposited onto buffered substrates covered by silver film and protected by copper stabilizer layers on both sides. The resistivity of the superconducting wire ρ_{HTS} is negligible during the normal operating conditions, hence $\rho_{HTS} = 0$ is applied. However, since the resistivity of superconductor is directly affected by the load current density and temperature, and the thermal conductivity of the superconducting tape is very low compared with conventional

conductors, the situation becomes complicated for the transient state when a fault current occurs.

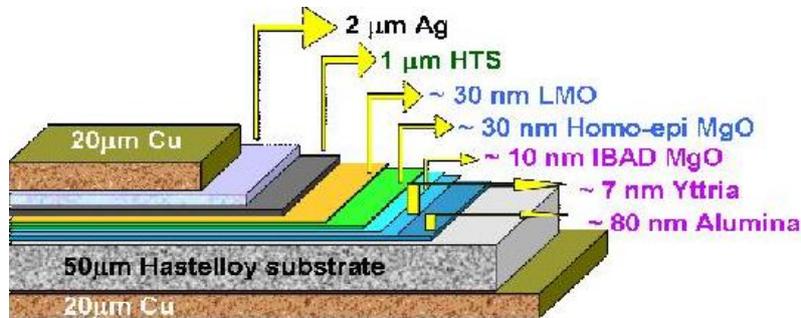


Figure 4.3: The configuration of superconducting wire

Figure 4.4 illustrates the load current flowing path inside the superconducting wire. From Figure 4.4 (a), it can be seen that the load current only passes through the zero resistance superconducting layer. Hence, the superconducting wire has zero resistance up to the critical current (maximum allowable current). On the other hand, the superconducting wires from some leading manufacturers introduce a high resistive layer into the superconducting wire, such as copper, stainless steel or brass. Once the load current is above the critical current, the load current will be diverted into the high resistive layer instantly, resulting to the high resistive state of superconducting wire, as shown in Figure 4.4 (b). Hence, the superconducting cable made of this kind of superconducting wire will have the ability to immediately limit the fault current magnitudes and decrease the X/R ratio in the network by insertion of a large resistance. In summary, the resistance of the superconductor is a variable parameter that is dependent on the load current. Hence, the coupling of superconducting tape resistivity with applied current and temperature becomes necessary in PSCAD/EMTDC superconducting cable model development.

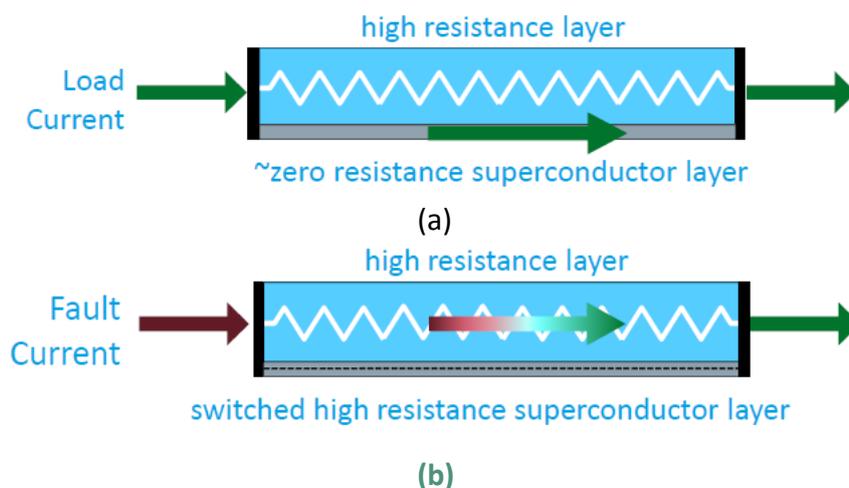


Figure 4.4: The schematic of the current path inside the superconducting layer

Additionally, the critical temperature and critical current are two important variables that directly determine the resistivity of superconducting tape.

4.4.2 The development of superconducting component in PSCAD/EMTDC

The superconducting component developed in PSCAD/EMTDC needs to be able to fully characterize the non-linear transition of the resistivity of the entire tape and describe the temperature profile. New component development in PSCAD/EMTDC requires a program based on Fortran language, which is very difficult for the user to compile and modify. However, a much more convenient method can be realized thanks to the PSCAD/EMTDC interface with MATLAB through standard Fortran programming. The characteristics of a new component in PSCAD/EMTDC can be programmed in MATLAB using the C language. In each calculation iteration, MATLAB is called by PSCAD/EMTDC. The relevant parameters in the PSCAD/EMTDC circuit are used as the input values for MATLAB and the output values from MATLAB are sent back to the PSCAD/EMTDC circuit for the next calculation iteration.

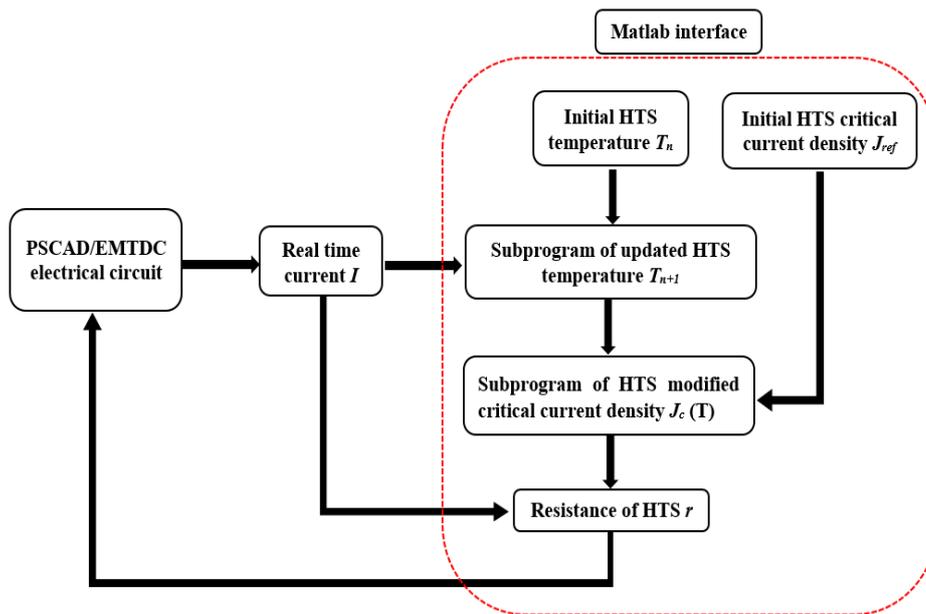


Figure 4.5: Flow diagram of the superconducting component calculation iteration in PSCAD/EMTDC interfaced with MATLAB

In the case of the superconductor model, the temperature and resistance of the superconductor are calculated in MATLAB based on the current values from the PSCAD/EMTDC circuit. As shown in Appendix I, the Eq. A.4 to Eq. A.11 are programmed in MATLAB in order to update the new resistance and the temperature, which are used to calculate the current and voltage of the superconductor in the next iteration. The duration of iteration step is set based on the PSCAD/EMTDC circuit simulation solution time step,

usually 25 μs is used. Figure 4.5 shows the flow diagram of the superconducting component calculation iteration in PSCAD/EMTDC interfaced with MATLAB.

4.4.3 The superconducting cable model development in PSCAD/EMTDC

Since the voltage rating of the superconducting cable installed in the network is 11 kV, based on the conclusion of the work package 1, the superconducting cable can be designed as three phase triaxial configuration, as shown in Figure 4.6 the three electrical phases are concentrically wound on the round cable former. The circulating liquid nitrogen is used to cool down the entire cable between 65 and 77 K. The electrical circuit model for the triaxial superconducting cable is shown in Figure 4.7. It consists of two sections: the section (a) is the PI section and the section (b) is the variable resistor. Table 4.6 summaries the main functions of the superconducting cable circuit model.

This PI section model is also used when the geometry of the transmission line is unknown, and it contains the information of the impedance and capacitance of the entire superconducting cable. However, the resistance of the PI section is constant, which is not the case for the superconducting cable. The resistance of the superconducting cable changes drastically when the load current exceeds the critical current or the operation temperature is over the critical temperature. Therefore, a variable resistor is introduced into the superconducting cable electrical circuit model. The initial value of the variable of the variable resistor is 0 ohm, and it is programmed by the Matlab. The detailed methodology for the variable resistor programming and interface with Matlab are presented in the appendix I.

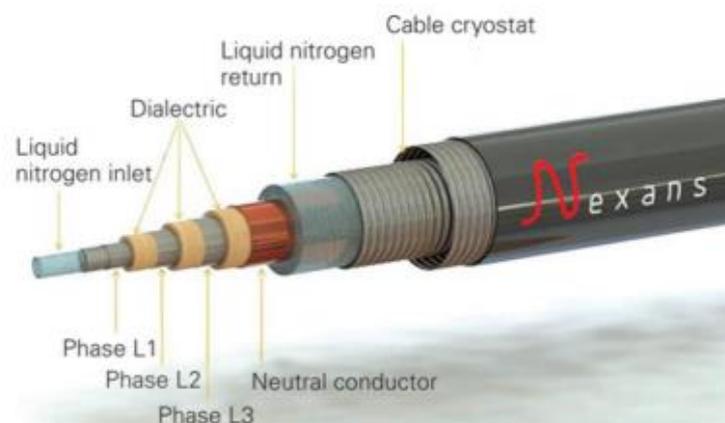


Figure 4.6: Triaxial configuration of superconducting cable proposed in the Substation-A

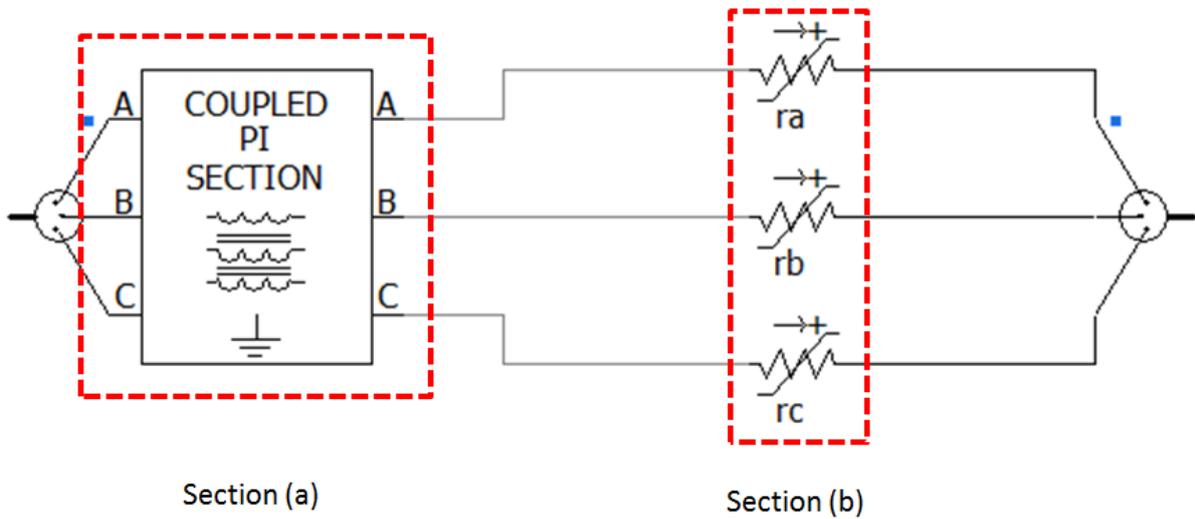


Figure 4.7: The electrical circuit model for the triaxial superconducting cable in PSCAD/EMTDC

Table 4.6: The summary of the superconducting cable circuit model

	Section (a)	Section (b)
Component	PI section model	Variable resistors
Description	Lumped parameter model transmission line	Resistance changes when the current is over the critical current, i.e., fault current applied
Function	Containing the	Transient-state superconducting cable model
Parameter	Resistance (R)	Variable resistor (ρ)
	Inductance (H)	
	Capacitance (C)	

4.5 Simulation results

4.5.1 Conventional solution

4.5.1.1 Power flow

Figure 4.8 shows the power flow of the conventional reinforcement solution for Substation-A. The red arrows show the direction of the power flow. The multi-meter in each branch shows the magnitude of the power flow. It can be seen that additional 40 MVA power is fed into the transformer at Bus 11 in the Substation-A via 132 kV distribution line, which is supplied by the Substation-D.

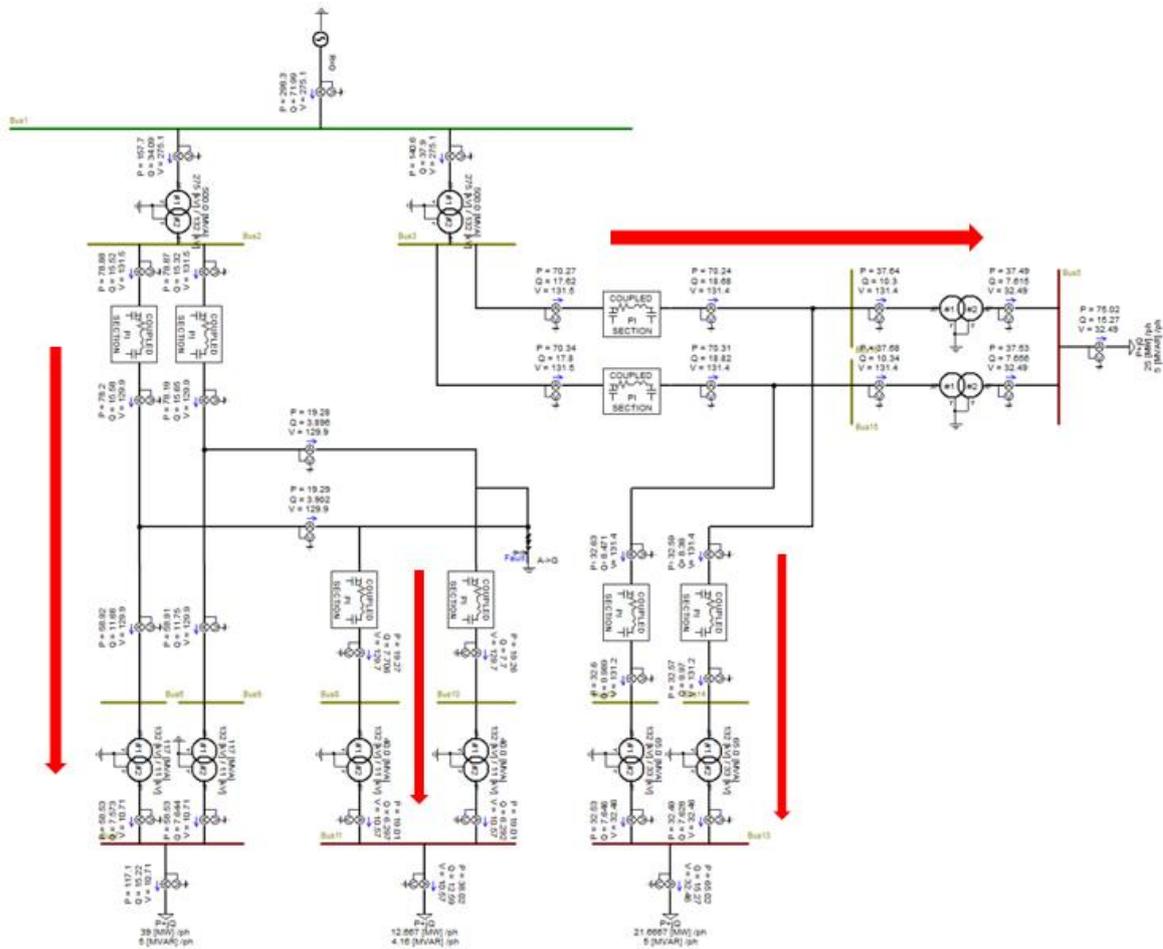


Figure 4.8: The power flow results based on the conventional reinforcement solution

4.5.1.2 Losses evaluation

Based on the power flow simulation, the resistive losses of the new installed 132 kV double circuits can be obtained. Losses incurred vary on a dynamic fashion depending on the power being transferred. The power demand in a particular substation varies a lot depending on the time of the day, day of the week, months and seasons. To simulate average operating conditions, 30% of full load has been considered for half year and 50% of full load for the remaining half of the year. The calculations for the load demand and losses generated are shown in Table 4.7 and 4.8 as below:

Table 4.7: Load demand at Substation-A, for 30% & 50% of full load, half year each

Total capacity	Power factor	P (MW)	Q (MVar)
12 MVA (30% load)	0.95	11.4	3.75
20 MVA (50% load)	0.95	19	6.24

Table 4.8: Losses incurred for 30% & 50% of full load, half year each

Power Input	Power Output	Instantaneous Loss	Losses integrated over half year
12.03 MW	12 MW	0.07 MW	324.14 MWh
20.07 MW	20 MW	0.14 MW	604.41 MWh
Total loss incurred over the entire year			928.55 MWh

4.5.1.3 Fault current level

In PSCAD/EMTDC, the fault can be simulated by connecting the fault component to the relevant circuit as shown in Figure 4.1. The magnitude and nature of the fault current depend on the following factors:

- The type of the fault
- The location of the fault
- The impedance of the fault

In order to simulate the random location, the PI section which is used to model the conventional line is separated into two sections, where the fault is applied between the two PI sections. When a fault is applied to the distribution line, it is equivalent to directly connecting the circuit to the ground with zero resistance.

The phase A to ground fault is applied to the 132 kV distribution line at the time of 0.1 s for the duration of 0.06 s. The fault current waveform is plotted in Figure 4.9. The peak level of the prospective fault current reaches 12.5 kA, as seen in Figure 4.9 and also summarized in Table 4.9. Notice that the current in the fault phase (illustrated in blue) consists of a large sinusoidal component superimposed a decaying DC offset. The magnitude of the offset is determined by the X/R ratio of the circuit. For the conventional solution, due to the fault current duration is relatively short, the impedance of the conventional circuits would keep constant resulting to a large X/R ratio in the grid.

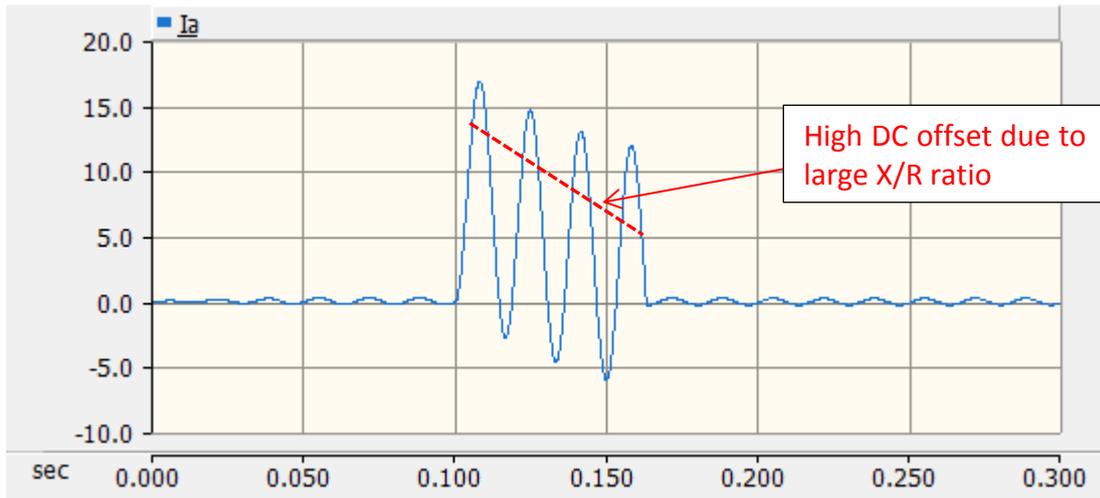


Figure 4.9: The current waveform of phase-A to ground fault

Table 4.9: The summary of the conventional cable circuit model

Operating Voltage and Load	Fault type and Duration	Limited Fault current magnitude & response time
132 kV, 40 MVA	Phase-A to Ground (0.06 seconds)	12.5 kA after 4 cycles

4.5.2 Simulation results of the reinforcement using superconducting cable solution

Alternatively, in order to reinforce the Substation-A, directly interconnecting 11 kV bus of the Substation-D and Substation-A could be considered, as no additional transformers or substations are required, which could be a very cheap solution. However, it is not feasible to implement with 11 kV conventional cables at distances larger than 2 km in urban locations, due to their high losses and significant voltage drop. The possible distance for the cable installation route between the Substation-D and Substation-A is about 5 km, therefore, directly using 11 kV conventional cable to interconnect both substations would not be considered.

However, the 11 kV superconducting cables can potentially enable the direct interconnection between the substations. 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. Figure 4.10 illustrates the 11 kV superconducting cable solution to reinforcement the Substation-A by Substation Direct interconnection. Note that a 132kV redundancy conventional cable is planned in parallel with the superconducting cable to be compliant with N-1 condition.

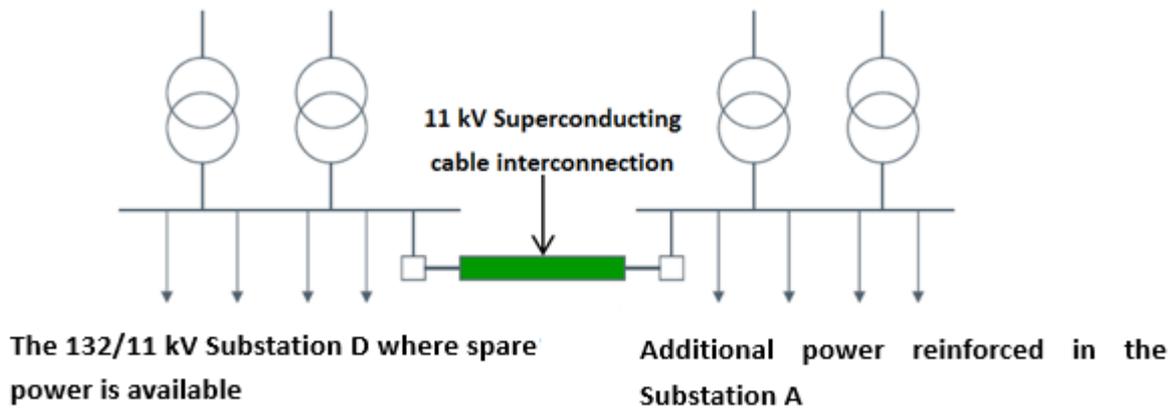


Figure 4.10: The schematic of superconducting cable solution for Substation-A reinforcement

4.5.2.1 Power flow

Figure 4.11 shows the power flow of the superconducting cable reinforcement solution for the Substation-A. It should be noted that the fault is not applied during the power flow study. In other words, the power flow study is based on the steady-state condition. The red arrows show the direction of the power flow. The multi-meter in each branch shows the magnitude of the of the power flow. It can be seen that additional 40 MVA power is directly fed into the load at Bus 11 in the Substation-A via an 11 kV superconducting cable, which is also supplied by the Substation-D. In this way, the 132/11 kV transformer substation is no longer needed, but the Substation-A can be reinforced the same as the conventional solution. Also, there is little impact on the power flow of other distribution circuits when the superconducting cable is installed, which indicates that the superconducting cable can be implemented in the distribution network in a way almost the same as the conventional cable.

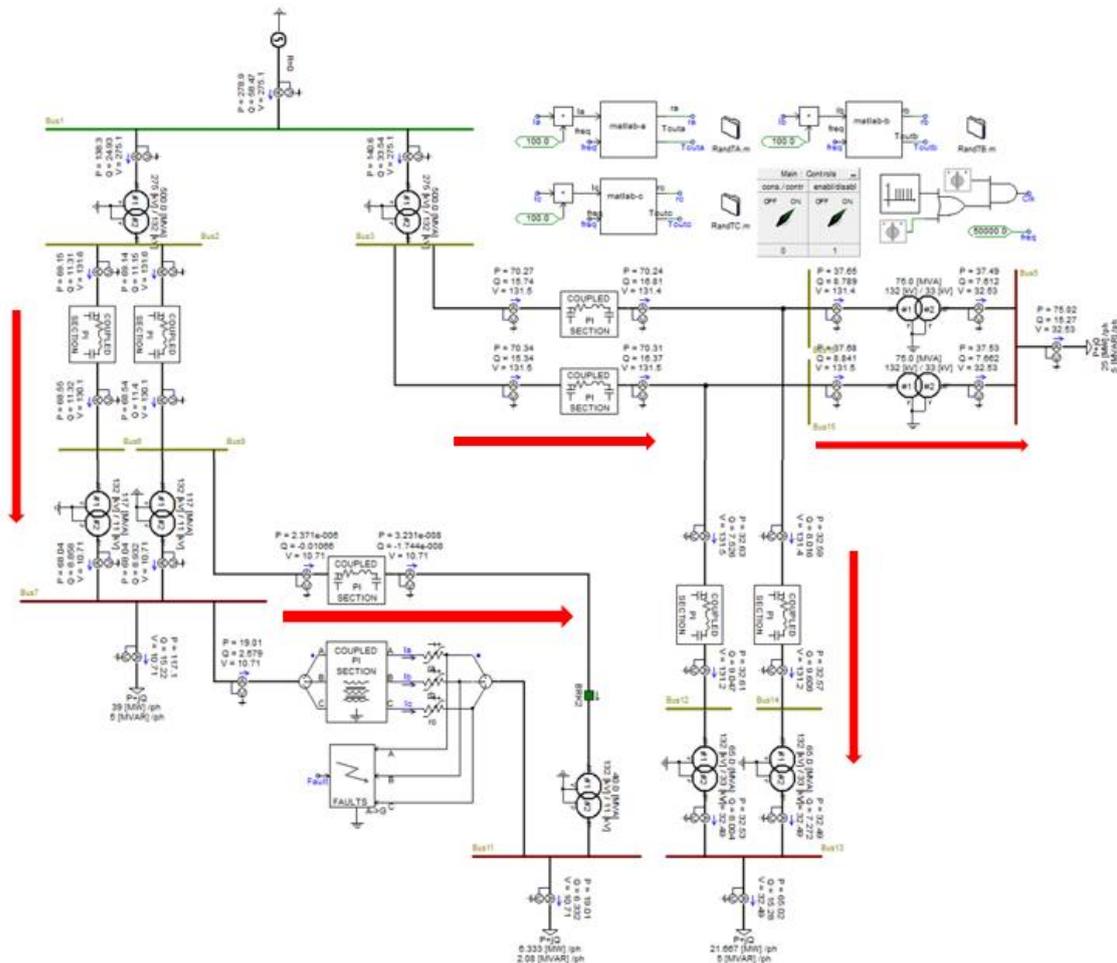


Figure 4.11: The power flow results based on the superconducting cable solution

4.5.2.2 Losses evaluation

Based on the power flow simulation, the resistive losses of the new installed 11 kV superconducting cable are also obtained. Even though the conventional cable is connected as a second infeed, limited by its huge resistive path, entire power required by the load demand will be transferred through the superconducting cable. However, same as the 132 kV conventional cable, the resistive losses of superconducting cable are also proportional to the I^2R . Thus, as the actual losses again depend on the load demand. To simulate average operating conditions, 30% of full load has been considered for half year and 50% of full load for the remaining half of the year and the concerned calculations for the load demand are summarized in the Table 4.7 previously. The losses incurred in the superconducting cable for the appropriate load demand are calculated as shown in Table 4.10 as below:

Table 4.10: Losses incurred for 30% & 50% of full load, half year each

Power Input	Power Output	Instantaneous Loss	Losses integrated over half year
12 MW (30% load)	12 MW	0.03 kW	133.15 kWh
20 MW (50% load)	20 MW	0.15 kW	665.76 kWh
Total loss incurred over the entire year			798.91 kWh

The total losses for the 30 and 50 % of the loads half year each, account to 798.91 kWh. This result is far less than the conventional cable by nearly 1000 times, which is due the low resistive path of the superconducting cable.

4.5.2.3 Fault current level

The fault applied to the superconducting cable is very similar with the simulation for the conventional solution present in section 4.5.1.3. The magnitude of the fault also depends on the location, impedance and type of the fault. Similar as the conventional simulation solution, in order to simulate the random location, the PI section which is used to model the conventional line is separated into two sections, where the fault is applied between the two PI sections. When a fault is applied to the distribution line, it is equivalent to directly connect the circuit to the ground with zero resistance.

However, due to the fault current is several times higher than the critical current of the superconducting cable, the resistance will increase drastically. The PI section is no longer adequate for the superconducting cable in fault current analysis due to the constant resistance and inductance in the component. In this case, the variable resistor is implemented and programmed by the Matlab based on the properties of superconducting wire and specifications of superconducting cable. The fault current of the superconducting cable can also be simulated in PSCAD/EMTDC by interfaced with Matlab.

The phase A to ground fault is applied to the 11 kV superconducting cable at the time of 0.1 s for the duration of 0.06 s. The fault current waveform is plotted in Figure 4.12. The peak level of the prospective fault current reaches about 20 kA. The variations of resistance of phase A and temperature of the superconducting cable are plotted in Figure 4.13 and Figure 4.14, respectively. For a brief understanding, the fault current magnitude, operating voltage and current are summarized in Table 4.11.

Notice that compared with the conventional solution, the DC offset current in the fault phase (illustrated in blue) has been significantly reduced. Since the magnitude of the DC offset is determined by the X/R ratio of the circuit, even the fault current duration is very short, the resistance of the superconducting cable increase immediately when the fault current is over the critical current of the cable, which results to a large X/R ratio in the grid. Additionally, the overall fault current is reduced by 50% with superconducting cable installed. Therefore, the reduced magnitude of fault current by using fault current limiting

superconducting cable is able to overcome the risk of substation damage due to high levels of fault current by conventional solution.

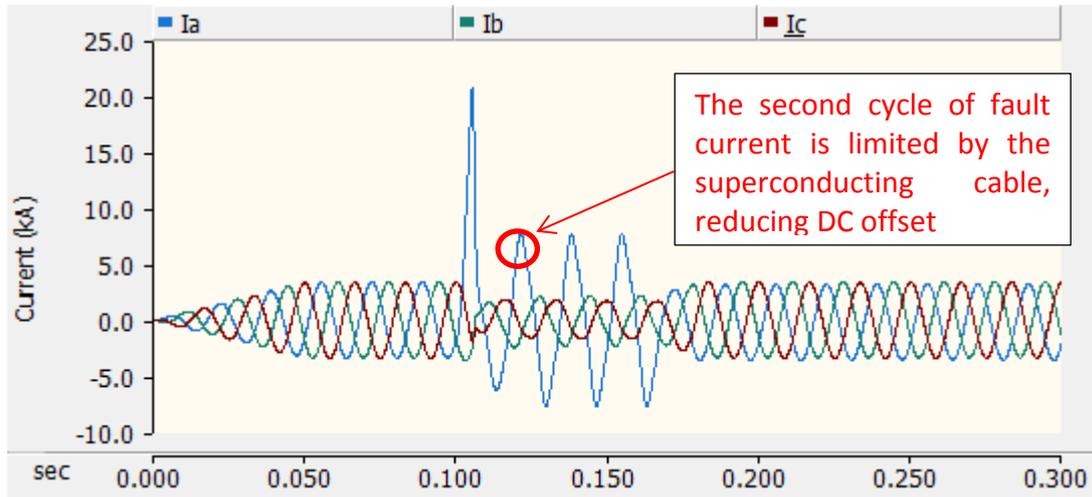


Figure 4.12: The current waveform of A phase to ground fault

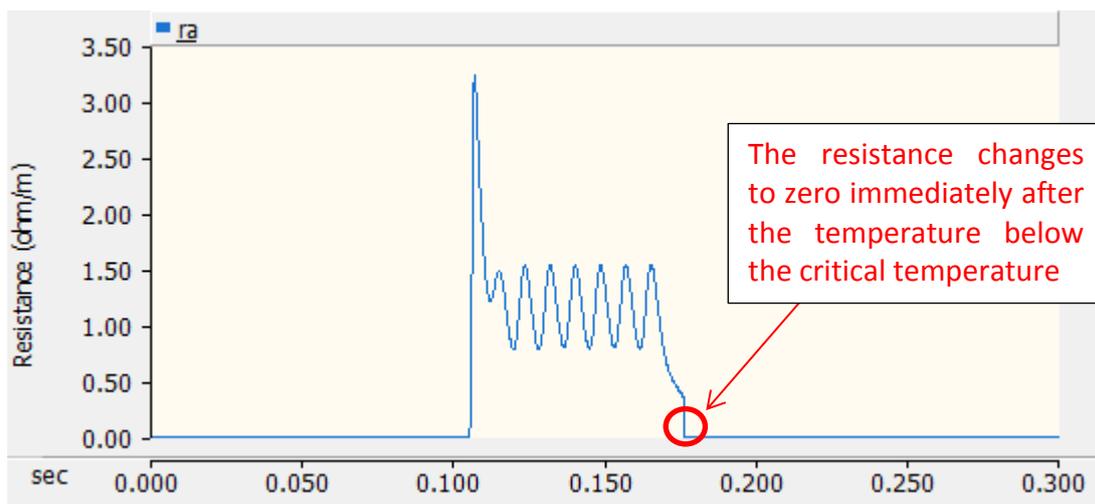


Figure 4.13: The resistance variation of phase A during the fault

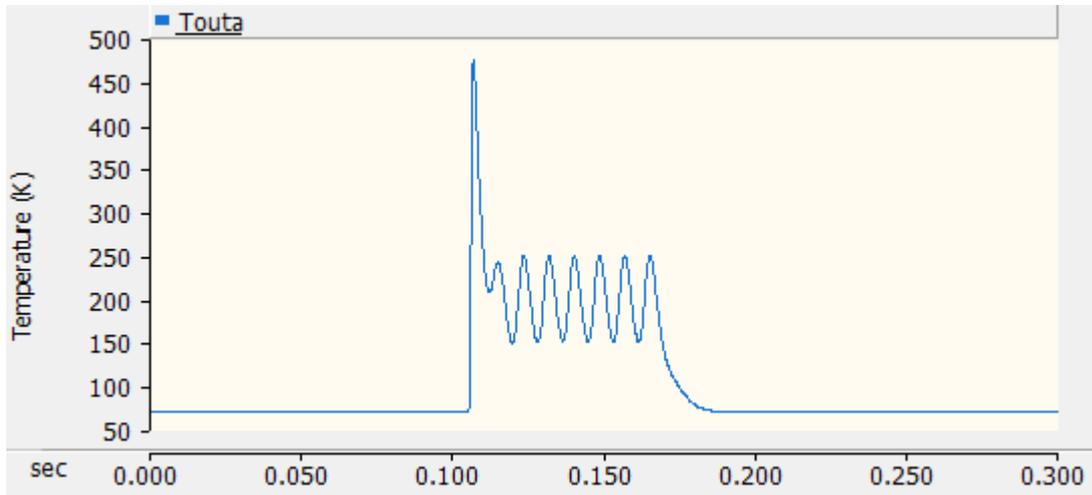


Figure 4.14: The temperature variation of superconducting cable during the fault

Table 4.11: The summary of the superconducting cable circuit model

Operating Voltage and Load	Fault type and Duration	Limited Fault current magnitude & Response time
132 kV, 40 MVA	Phase-A to Ground (0.06 seconds)	8 kA with in a half cycle.

4.6 Comparison of conventional solution and superconducting cable solution based on the simulation results

- For power flow: the conventional solution and superconducting cable solution has the similar power flow fashion, which indicates that it is unlikely to have a drastically change of power flow, if the superconducting cable is installed in the distribution network. The impact of the superconducting cable on the other distribution circuits is also negligible in the distribution network.
- Based on the resistive losses results, the total resistive losses of the simulated distribution network for conventional cable is much higher than the superconducting cable solution.
- Table 4.12 shows the losses of 132 kV conventional cable system and 11 kV superconducting cable system, respectively. The losses are obtained based on the PSCAD/EMTDC simulation results, while the load at bus 11 is assigned as 9 MVA for half year and 20 MVA for the half year.

Table 4.12: The losses of conventional and superconducting solutions for the 30 and 50 % of load demand for half year each

	Losses incurred
Conventional solution	928.55 MWh
Superconducting solution	798.91 kWh

- When the fault is applied, the 11 kV superconducting cable has the ability to reduce the DC offset and limit the fault current by 50 % while the 132 kV conventional cable will have a relatively high fault current with a large DC offset.

4.7 Summary

The performance and influence of the reinforcement work for Substation-A are discussed based on power system simulation software PSCAD/EMTDC. The methodology of the superconducting cable model is discussed in detail. The simulation circuits of the distribution network for both conventional solution and superconducting cable solution are presented and the simulation results of power flow, fault current level and resistance losses are analyzed.

Overall, based on the simulation study, it is known that both the conventional solution and superconducting cable solution are adequate enough to reinforce the Substation-A. The additional 40 MVA power required, could be supplied by either 132 kV conventional cables combined with 132/11 kV transformers or one 11 kV superconducting cable and one conventional 132kV infeed along with a 132/11kV transformer.

Chapter 5

Cost and Benefit analysis

5.1 Introduction

This chapter aims to perform the cost and benefit analysis (CBA) for Substation-A reinforcement project, which considers the two available technologies as potential solutions:

- i. 132 kV conventional cable solution
- ii. 11 kV superconducting cable solution

This CBA is based on the detailed technology design presented in Chapter 3 and distribution network simulation presented in Chapter 4. The results of the CBA are used to assess which of above technologies is best to solve the capacity problem of the case study.

5.2 Costs

This section will take into account all costs of conventional cable solution and superconducting cable solution, respectively. The cost includes both initial capital investment cost and recurring costs (or operating cost). The initial capital investment cost of conventional solution is provided by WPD and the initial investment cost of superconducting cable solution is provided by a superconducting cable manufacturer. The recurring cost (operating cost) lasts annually over the entire lifetime of the cable. Usually, cables have a lifetime of around 40 years, the actual value of money might be changed annually during this period of lifetime. Hence, multiple costs to be incurred every year in the future could be calculated and indicated by a present value (current money), for which an inflation discount could be considered to define future costs in present money. In other words, this calculation brings the cost into present value in pounds, so that it is possible to compare the total costs between the conventional cable and superconducting cable solution in today's money.

5.2.1 Non-Recurring Costs

This section will present the non-recurring cost of conventional cable and superconducting cable solution, respectively. In this case, the non-recurring cost refers to the initial investment cost. This section presents the initial capital investment cost of conventional solution and the alternative superconducting cable solution for Substation-A reinforcement project.

5.2.1.1 Initial capital investment cost for conventional cable solution

The initial capital investment cost for conventional cable solution is provided by WPD and the detailed breakdown costs are shown in Table 5.1. The capital cost of conventional cable solution includes:

- a. Completed 132 kV conventional cable.
- b. The 132/11 kV transformers cost.
- c. Civil work regarding the cable installation.
- d. Cable joints box.
- e. The land cost.

Table 5.1: Conventional solution capital investment cost

Conventional solution capital investment cost	
Description	Cost
Land 132 kV	£408, 024. 00
Land Purchase at Substation-D	£140, 000. 00
Civil 132 kV	£1, 814, 395. 00
P+M 132 kV	£3, 691, 142. 00
Cable Laying Contract 132 kV	£3, 993, 082. 36
Cable Supply 132 kV	£3, 227, 596. 08
Cable Jointing 11 kV	£23, 057. 38
Cable Supply 11 kV	£114, 032. 25
11 kV Cable Laying Contract	£142, 467. 30
Cable Supply LV	£8, 953. 00
Total	£13, 562, 749. 37

From the Table 5.1, it can be seen that the total initial capital investment of conventional cable solution is £13.5 million. It is usually recommended to invest such high capital costs in 2-3 calendar years, so as to ensure that the allocated capital is spend appropriately, as shown in Table 5.2.

Table 5.2: The initial capital investment of conventional cable over 3 calendar years

Initial capital cost of conventional cable			
	1st year cost	2nd year cost	3rd year cost
Total capital cost	40%	40%	20%
£13, 562, 749	£5, 425, 100	£5, 425, 100	£2, 712, 550

It should be noted that the cost of Substation-A above only shows a specific case, i.e. Substation-A reinforcement project. However, the cost could vary significantly among different projects.

5.2.1.2 Initial capital investment cost for superconducting cable

The initial capital investment cost for superconducting cable solution includes:

- i. Completed superconducting cable system package quoted from the vendor.
- ii. Civil work regarding the cable installation.
- iii. Cable joints box.
- iv. One-off LN₂ cost.
- v. The land cost.
- vi. A redundancy conventional 132kV cable and related equipment.

The superconducting cable system package cost is provided by a superconducting cable manufacturer. The costs of civil work and the joint box are provided by WPD. The one-off LN₂ cost for cooling system is estimated based on the operating experience of superconducting cable supplier.

The cost of land is calculated based on the land area required, assuming 5 x 10 m² for 11kV switch room, termination, control room, cooling system and all other components. The land cost per m² is calculated from the unit land price of urban area: £113.34/m². Table 5.3 gives the land cost for superconducting cable solution.

Table 5.3: The land cost for superconducting cable solution

	Area of land required (m ²)		cost per m ²	Total land cost
Superconducting cable solution	Switch room	50	£113.34	£10,461.85 + £208,000.00 (for transformer to be used in redundancy plan)
	Cable termination	3.2		
	Cooling system and control center	18		
	SFCL	20.105		
	Total area	92.305		

Based on the aforementioned methodology, the capital investment cost of superconducting cable solution is shown in Table 5.4, with the detailed breakdown cost.

Table 5.4: Superconducting cable solution capital investment cost

Superconducting cable solution capital investment cost		
Description		Cost
Purchase a completed package of 11 kV 5 km superconducting cable system		
Include 9 joints and 2 terminations		
Installation of the superconducting cable and the sFCL		
Commissioning of the superconducting cable and the sFCL		
Cooling station for cable and sFCL		
Factory test		
Transport to the site, packaging, drums		
	Subtotal	£16,300,000.00
One off LN ₂ cost		£5,000.00
Land		£218,461.85
Civil work		£156,000.00
Cable Jointing 11 kV		£23,057.38
11 kV Cable Laying Contract		£142,467.30
P2/6 132 kV redundancy circuit		£6,504,476.00
	Total capital cost	£23,349,462.53

From the Table 5.4, it can be seen that the total initial capital investment of conventional cable solution is £23.3 million, and it is divided into 3 calendar years to invest, as shown in Table 5.5.

Table 5.5 The initial capital investment of superconducting cable over 3 calendar years

Initial cost of superconducting cable			
	1st year cost	2nd year cost	3rd year cost
Total capital cost	40%	40%	20%
£23,349,462.53	£9,339,785.01	£9,339,785.01	£4,669,892.51

5.2.2 Recurring Costs

This section presents the recurring cost of conventional solution and superconducting cable solution for Substation-A reinforcement project over the expected lifetime of respective technologies. The recurring cost is mainly contributed by daily operating and maintenance cost. The worst scenario of cooling cost is considered for superconducting cables.

5.2.2.1 The recurring cost for superconducting cable

Since the superconducting cable requires to be operated around 70 K, cooling power must be provided. A worst scenario i.e. retail price £9.7p/kWh is used to calculate the cooling cost of the superconducting cable. For the closed loop superconducting cable system, electricity is consumed by refrigerator or cryocooler daily, which forms the major contribution of operating cost. Table 5.6 shows the operating cost for superconducting cable at full load (100 kW cooling power).

Table 5.6: Operating cost for superconducting cable at full load

Operating cost for superconducting cable		
Description	Cost of cooling per unit	cost per annual
Electricity	£9.7p/kWh	£84,972.00

5.2.2.2 The recurring cost for conventional solution

It has been discussed that excluding the losses, there is no significant recurring cost, i.e., the operating cost, for conventional solution in this case. Therefore, the recurring cost for conventional solution will not be taken into consideration.

5.3 Benefits

Based on the conventional solution as a reference, this section will assess the benefits of superconducting cable solution, in order to understand and specify whether it is sensible to consider superconducting cable as a potential alternative solution for Substation-A reinforcement project or not.

5.3.1 Non-Recurring quantifiable benefits

The non-recurring benefits mainly contains two parts for alternative superconducting cable solution:

- i. The cost reduction in initial capital investment by implementing superconducting cable system with reference to conventional solution, which can be quantified with a value in pounds.
- ii. The positive impacts that can improve the performance and efficiency of cable system, hence enhancing the value of the investment, which cannot be quantified.

5.3.1.1 Removing the need for urban substation

Since the conventional solution utilizes 132 kV distribution voltage, a complete 132/11 kV substation is required to be constructed, which mainly involves the cost of transformers, circuit breakers and switch gears. However, the 11 kV superconducting cable can realize a direct interconnection between the substations, enabling significant cost reduction.

5.3.1.2 Reduced civil engineering cost

Pertaining to the compact structure of superconducting cable system, the cable can be installed a smaller cable trench or duct. Additionally, there is no electromagnetic and thermal impact on the surrounding environment, thus posing a possibility of significant reduction in the clearance requirements for superconducting cable. Hence, the overall civil engineering cost for superconducting cable could be much lower than equivalent conventional solution.

5.3.1.3 Less land space required

Superconducting cable requires less space than conventional cable, leaving extra room for new generation and load growth. Additionally, the superconducting cable termination is extremely compact, which only requires a small land area.

5.3.1.4 Longer lifetime of superconducting cable

Superconducting cables have potentially longer lifetime, thanks to continuous heat absorption of the LN₂, and hence less degradation on PPLP dielectric. It is estimated to have over 40 years of lifetime, which is longer than the lifetime of conventional cable. Hence, it is possible to save the whole capital investment cost of conventional solution for Substation-A reinforcement over 40 years' time.

5.3.2 Recurring Quantifiable Benefits

Losing part of the electricity is an inevitable consequence, while transferring electricity across the distribution network, introducing a significant financial and environment impact on the end users. In 2013, as a proportion of demand on GB's networks, losses were estimated to be 7.2 percent – 27 TWh. Losses can be split into three components: transmission losses, distribution losses and theft, demonstrated in Figure 5.1. Distribution networks account for the majority of electricity network losses, as cables being operated at lowered voltage and at high ampacity levels.

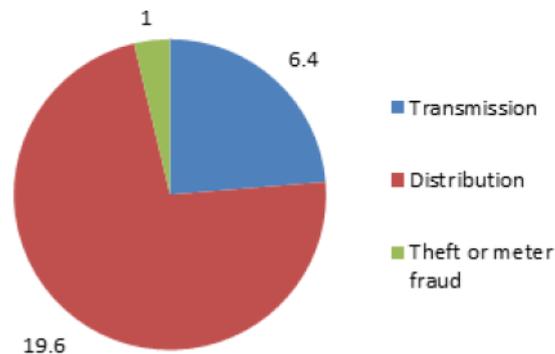


Figure 5.1: Total electrical losses split between transmission networks, distribution networks and theft in 2013 (TWh)

Ofgem has introduced a loss reduction mechanism into DNOs’ price control agreement, with the aim of encouraging DNOs to find out cost-effective loss reduction measures. Superconducting cable is one of the solutions, capable of reducing the losses and save significant cost on losses. As there are reduced losses for superconducting cable, each year DNOs can save a significant amount of money on the losses. The cost of losses is evaluated to about £48/MWh [2]. The estimated reduction in losses by implementing superconducting cable will be further analysed in section 5.3.4.

5.3.3 Non-Quantifiable Benefits

5.3.3.1 No electric and magnetic field (knows “EMFs”) impact

There have been growing concerns expressed by public, regarding potential health effects of power-frequency EMFs, emitted by electric transmission and distribution lines and substation equipment. Currently, the UK Government is considering possible options for reducing public exposure to EMF from distribution systems. Fortunately, superconducting cables will be a promising solution for this particular issue. In the design of superconducting cable, the inner layers of superconducting tapes transmit power while the outer layers are grounded. In the outer layers, currents equal in magnitude with inner layers but opposite in phase are induced. These induced currents completely eliminate the electromagnetic fields of the inners layers. Hence, superconducting cable is capable of delivering power while generating no external magnetic fields, which makes it more environmentally friendly.

5.3.3.2 Pathway for future electricity distribution networks

The UK Climate Change Act established a target for the UK to reduce CO₂ emissions by at least 34% by the year of 2020 and greenhouse gasses emissions by at least 80% by 2050. To ensure that regular progress is made towards this long-term target, Ofgem introduced the Low Carbon Network (“LCN”) concept to guide DNOs to test new technology and commercial arrangement to support the UK’s low carbon transition and climate change objectives. Thanks to the negligible losses, superconducting cable is able to effectively eliminate the inefficiencies in power distribution network, paving the way towards

decarbonization of electric distribution network. If the superconducting cables were implemented in the UK’s distribution network, there could be a huge reduction of CO₂ emission over a range of hundreds of tons yearly.

5.3.3.3 Enhance the grid flexibility and distribution reliability

As shown in Figure 5.2, the superconducting cable can serve as a bus link between the two substations, increasing grid flexibility and system security. Additionally, superconducting cable can enable interconnection between the substations with less space than conventional cable, leaving room for future load growth.

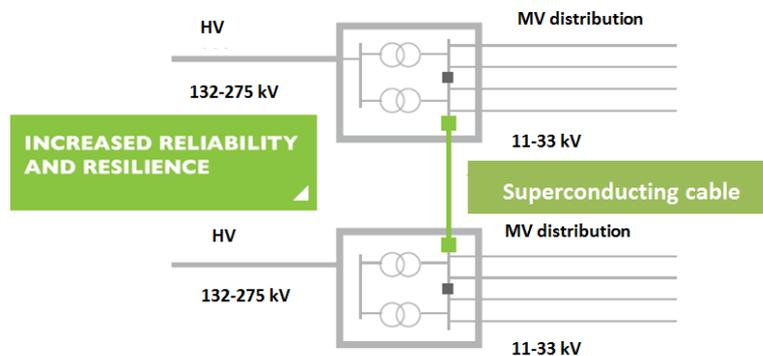


Figure 5.2: Superconducting cables provide high-capacity distribution-voltage links between substations

5.3.3.4 Interconnecting substations with fault current limiting capabilities

As shown in Figure 5.3, superconducting cable can limit the fault current level and hence enhance the fault current limiting capacity while interconnecting the urban substations.

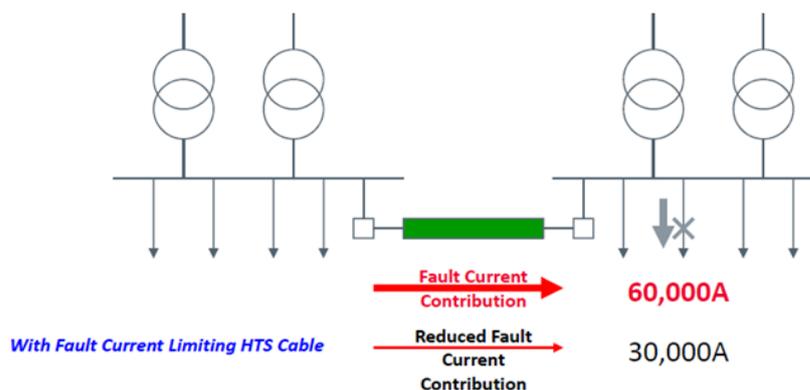
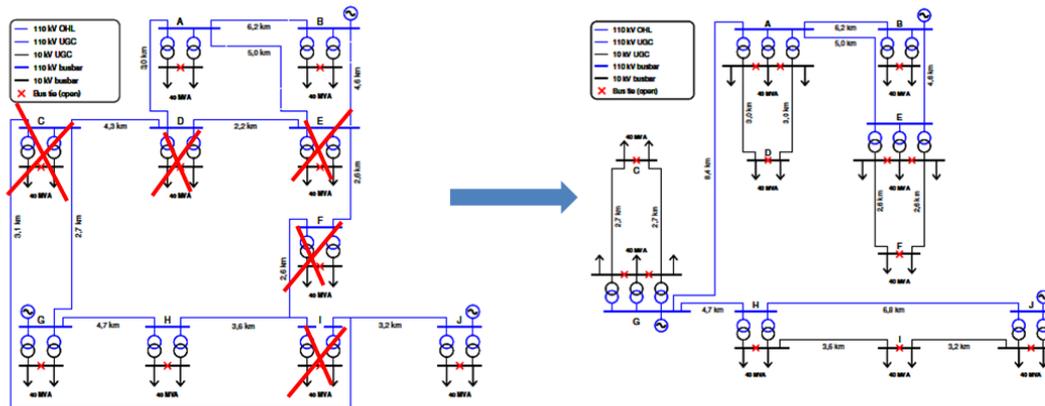


Figure 5.3: Interconnection between urban substations with fault current limiting superconducting cable

5.3.3.5 Enable a new LV network architecture by removing transformers

As shown in Figure 5.4, the number of urban substations can be minimized by using low voltage superconducting cables, resulting in a distribution network with less urban substations.



(a) Conventional high voltage distribution network

(b) Superconducting cable low voltage distribution network

Figure 5.4: A new superconducting cable LV network architecture by removing transformers

5.3.3.6 Less operating noise

The 132 kV conventional cable requires 132/11 kV substation in place to distribute electric power. In a residential area, the noise of the transformers inside the substation will cause a significant interruption to the residents. However, superconducting cable system will minimize the operating noise by removing the need for high voltage transformers in the substation so that it can keep the interrupt to be minimal.

5.3.4 Net present value analysis

In order to quantitatively perform the cost benefit analysis of the conventional solution and the alternative superconducting cable solution for Substation-A reinforcement, it will quantify the costs and the benefits in terms of pounds based on the methodology of net present value of cost.

Based on the value of money w.r.t. time, money in the present is worth more than the same amount in the future. This is both because of earnings that could potentially be made using the money during the intervening time and because of inflation. In other words, one pound earned in the future won't be worth as much as one earned in the present. To include this concept, the following equation is adopted in the present value calculation:

$$PV = Capital\ cost + \frac{FV}{(1 + i)^n}$$

$$FV = Losses + Operating\ cost$$

$$\text{Operating cost} = \begin{cases} 0 & - \text{ for Conventional cable} \\ \text{Cooling cost} & - \text{ for Superconducting cable} \end{cases}$$

where,

- PV is the present value
- FV is the Future value, comprising of both losses cost and operating cost
- i is the decimal value of the discount rate for a specific period
- n is the number of periods between present and future

Future value (FV) includes the profit incurred from the transmitted power and also the loss incurred due to power losses, maintenance etc. Discount rate is used to convert all costs and benefits to ‘present values’, so that they can be compared. The recommended discount rate of 3.5% by the UK government had been utilized in the current study [4]. Calculating the present value of the differences between the streams of costs and benefits provides the net present value (NPV) of an option.

In this study, the following results present the results of present value of cost for conventional solution and superconducting cable solution, respectively. The cost of electricity also affects the results of the CBA results, in this analysis, the operating costs per unit are adapted to perform the CBA analysis, as shown in Table 5.7.

Table 5.7: Operating cost per unit

Cost of losses [2]	Cost of cooling (retail price) [3]
4.8p/kWh	9.7p/kWh

Additionally, the cost of the losses for both conventional and superconducting cables is calculated as shown in the equation below, while the operating cost of superconducting cable is calculated based on the cooling power as shown in Table 5.6.

$$\text{Ongoing costs} = \text{Losses integrated over the year (in kWh)} \times \frac{4.8p}{kWh}$$

Figure 5.5 shows the calculation results for the present value of cost of the Substation-A regarding the 132 kV XLPE cable and superconducting cable, respectively. The present value of cost for the project considers the summation of capital cost and operating cost over the pre-determined lifetime with a discount rate of 3.5%. For a better comparison, it is assumed that both 132 kV conventional cable and 11 kV superconducting cable will have the same lifetime up to 40 years. Based on results in the figure 5.5, it can be seen that the total cost of 11 kV superconducting cable solution is around £10 million more than the 132 kV conventional cable solution, which is mainly due to the cost of expensive superconducting materials.

Figure 5.6 shows the trend of present value of cost for 11 kV superconducting cable solution and 132 kV XLPE conventional solution, respectively, with 40 years of service lifetime. As

expected, the losses of superconducting cable are negligible, which leads to a very stable present value of cost over the 40 years’ service time with increased load factor. For the system where the load factor is high, the cost of losses will also be higher leading to increased present value of cost.

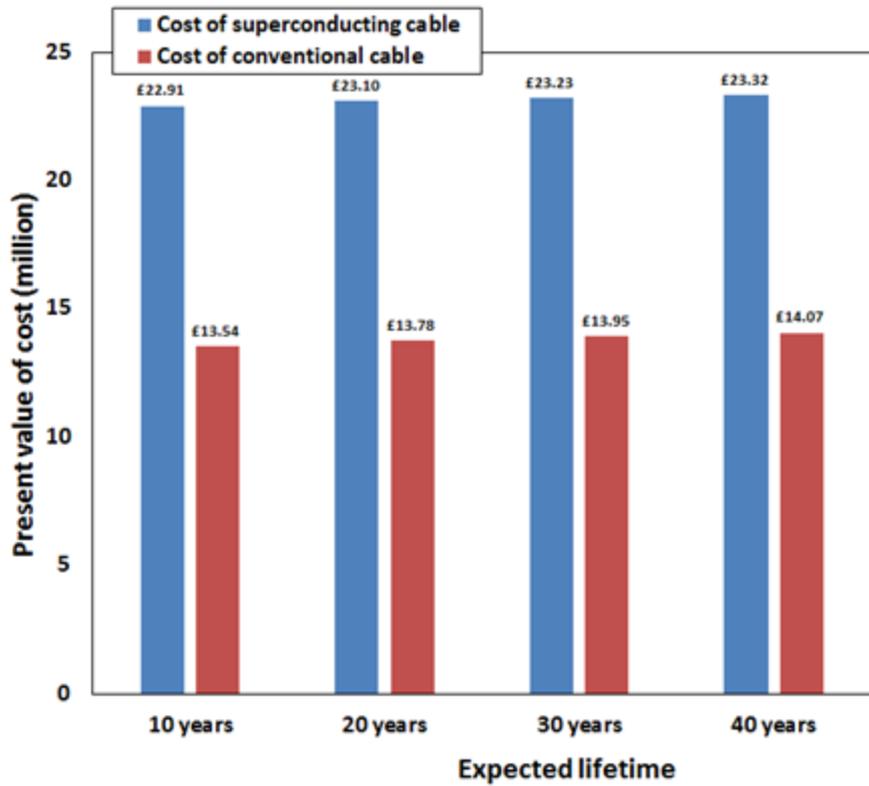


Figure 5.5: Present value of cost over the entire lifetime

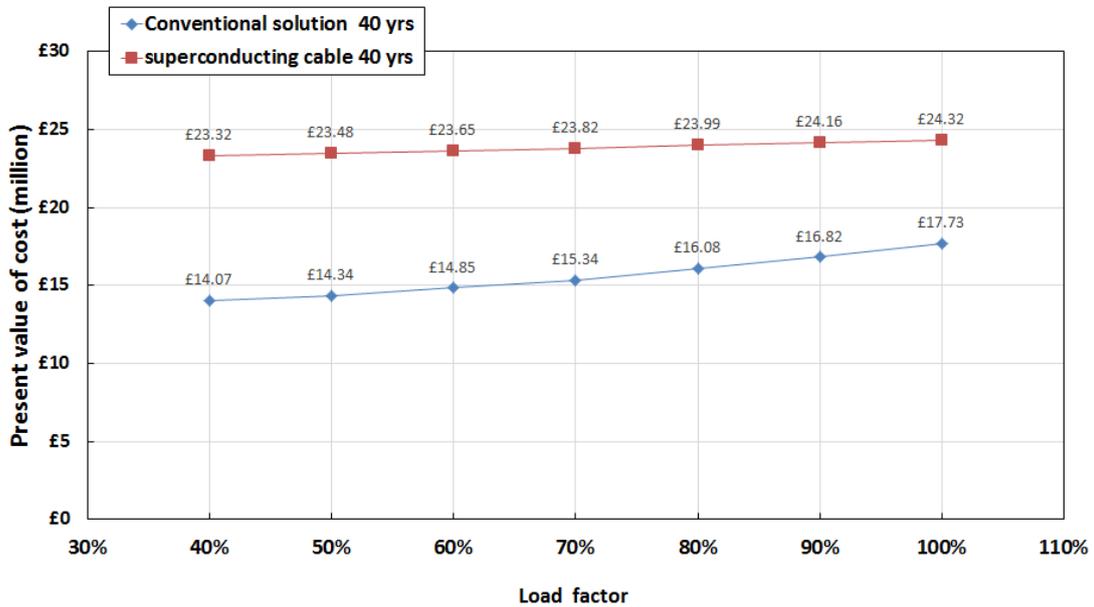


Figure 5.6: The present value of cost with varied with load factor

5.4 Summary of cost and benefit analysis

Table 5.8 summarizes the CBA analysis of the Substation-A reinforcement project.

Table 5.8: The summary of CBA of the Substation-A reinforcement project

No.	Parameters	Brief description
1	Removing the need for urban substation	Capable of transferring High - power capacities at lower voltage levels, eliminated the need for one or more transformers and the associated auxiliary equipment's.
2	Simplified civil works	By avoiding high voltage cables, effort required for large trenches gets reduced. Similarly, safety requirements also get bit simplified, reducing the overall cost.
3	Smaller land required	The land required for 11 kV superconducting cable is significantly reduced
4	Lower operating cost (lower losses)	Considering the losses and power required for the cables to operate, the operating cost of superconducting cables is lower than both conventional and overhead lines. This is considering that most of the power in the superconducting solution would be provided by the Superconducting infeed as its impedance is lower, hence having significantly lower losses.

5	Longer lifetime	Superconducting cables have potentially longer lifetime, thanks to continuous heat absorption of the LN ₂ , and hence less degradation on PPLP dielectric.
6	Increased Capital Cost	Superconducting material being expensive, the resultant superconducting cable is £7.6 million more expensive than the corresponding conventional cable solution.
7	No electric and magnetic field (knowns “EMFs”) impact	Superconducting cable is capable of delivering huge power, while generating no external magnetic fields, which makes it more environmental friendly.
8	Pathway for future decarbonization of electric distribution networks	Superconducting cable is able to effectively eliminate the inefficiencies of the power distribution networks, which has been proved and can pave the way for decarbonization of electric distribution networks.
9	Enhance the grid flexibility and distribution reliability	Superconducting cable enables interconnection between the substations with less space than conventional cable, leaving room for next generation and load growth
10	Interconnecting substations with fault current limiting capabilities	Superconducting cable either by itself or coupled along with fault current limiters, enhances the fault current limiting capacity.
11	Enable a new LV network architecture by removing transformers	The number of urban substations can be minimised by using low voltage superconducting cables.
12	Less operating noise	Superconducting cable system will minimize the operating noise due to the removal of high voltage transformers in city centres.

Chapter 6

Superconducting cable in the future

The CBA analysis in Chapter 5 is based on the current price of superconducting cables and also for the specific case. The cost scenario can differ slightly when it comes to reality, depending on the kind of redundancy plan chosen, year of installation and competitive spirit among the superconducting cable manufacturers, as the technology being new. This chapter will briefly discuss the cases, where superconducting cables can be more cost effective considering all other possible scenarios. It will also take into account the future price reduction of superconducting cables [5].

6.1 Specific cases where conventional solutions are prohibited

Due to geological, environmental and space constraints, there may be some cases where conventional solution is prohibited. These include

- i. Prohibition of 132 kV conventional cable implementation**
Due to the requirement of large clearance distance of 132 kV cable, it may not be possible to install 132 kV underground conventional cable.
- ii. Limitation of power capacity expansion in medium voltage (11 to 33 kV)**
Due to the high losses of copper cable, to expand the power capacity may not be feasible by using medium voltage cable.
- iii. Limitation of substation construction in urban areas**
Due to high voltage (>33 kV) equipment restriction, it may not be possible to construct 132 kV level substation in some urban areas.
- iv. Limitation of open installation**
Due to the electromagnetic and thermal impact of high voltage (>33 kV) copper cable, it is not possible for conventional cable to realize open installation, such as cross the bridge.

Superconducting cable stands out as a sole technology that could be used to address the above limitations.

6.2 The future price reduction of superconducting cable solution

Compared with the current price of superconducting wire of £400/kA-m, the price of superconducting wire could be 100 times less than the current price. As pointed out in [5] the price of superconducting wire can decrease from £400/kA-m today to only £4/kA-m and it is estimated that this should occur in the time frame between 2025 and 2030 [5]. Based on the future price of superconducting wire, we have performed CBA analysis for Substation-A reinforcement project. It has been observed that with reduced price of superconducting wire, there is a huge cost saving by implementing 11 kV superconducting cable compared with 132 kV conventional XLPE cable. Note that in this analysis, there are two 11 kV superconducting cable implemented to fulfill n+1 redundant security

requirement. The superconducting cables price is observed to be about half the price of conventional solutions, if the price can be reduced according to [5].

6.3 Reduced cooling cost

Since superconducting cable requires cooling power at all times, cooling cost for cryocoolers makes a significant contribution on the total operating cost. However, due to the operating cost of cryocoolers in terms of the consumption of electricity, it could be possible to reduce the operating cost by choosing a cheaper supplier, directly negotiating with suppliers from the wholesale market etc. Compared with 9.7p/kWh cooling cost, if the cooling cost could reduce to 6p/kWh or 4p/kWh, the total operating cost over 40 years’ service time can be reduced significantly, as shown in Figure 6.1. Therefore, superconducting cables should be used in where cheap cooling electricity can be obtained.

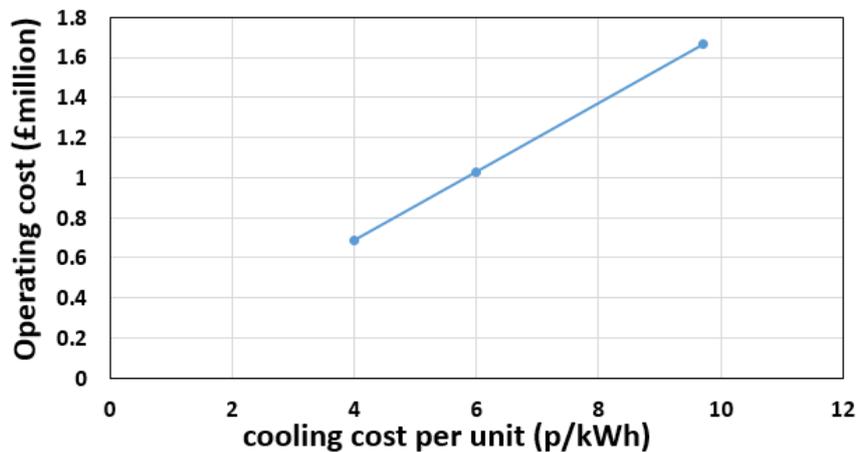


Figure 6.1: The total operating cost with reduced cooling cost

6.4 Increased power demand

The main advantage of implementing superconducting cable compared to copper cable is to achieve the saving on cost of resistive losses. The resistive losses is proportional to current, which means higher load demand will result to higher losses. Hence, in the case of heavy load demand, the superconducting cable is able to saving significant cost of losses in the network as shown in Table 6.1.

Table 6.1: Losses incurred based on Load demand

	Average loading	100 % loading
Conventional Solution	928.55 MWh	4749.36 MWh
Superconducting solution	798.91 kWh	7.99 MWh

Based on the case of Substation-A reinforcement project, if the load demand of Substation-A is increased from 40% to 100% of total 40 MVA load, the total saving on operating cost over the 40 years’ service time is shown in Figure 6.2 (considering 9.7p/kWh cooling cost). It can be seen that the total saving of operating cost for superconducting cable is increasing quadratically with the load factor. Therefore, superconducting cables should be best used in places where there is a need for utilising cables at near full load most of the time. For example, cables operating for interconnecting generators and transmission network usually operate at near full load, which can be an ideal place for utilising superconducting cable.

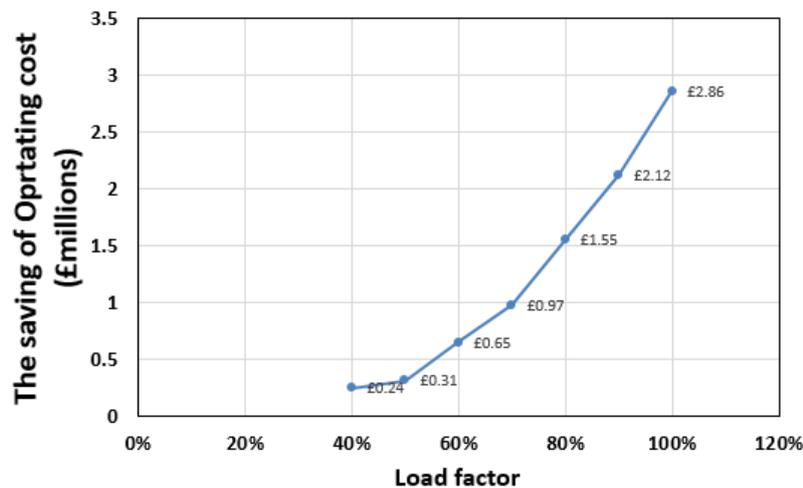


Figure 6.2: The saving of operating cost of superconducting cable over the 40 years’ service time

6.5 Reduced cable length

It is known that in the case we studied, the majority of the cost for superconducting solution is coming from the superconducting cables whose cost is approximately proportional to the length of the cables. If the cable length is reduced, the overall cost can also be reduced. However, for the conventional solution, 27% of the capital cost is from the substation of the transformers which are not related to the cable length. Even when the cable length is reduced, the overall cost wouldn’t be reduced as much as in the case of the superconducting solution.

The price of both superconducting cables and conventional cables are assumed to increase/decrease linearly to the cable length, but the cost of the transformers is kept as the same, which is very near to ideal case. When the cable length is reduced to 2 km, the capital cost of the superconducting solution is £4,600,332.34 while the conventional solution is £7,728,441.19. Therefore, superconducting cables should be used to transfer power from a neighboring substation with a relatively shorter length.

6.6 Summary of the preferable cases for superconducting cable implementation

Based on the above analysis, the preferable cases for superconducting cable implementation is summarised as follows:

- i. Heavy load situations, such as power plant, data centre or factories.
- ii. Less length of cable required in high power demand area, such as the power cable between power plants and step-up transformers in the power plant.
- iii. Space limited area, such as inner city where no more space is able to facilitate multiple conventional cable installation.

Chapter 7

Summary, Key Outputs and Next Steps

7.1 Summary of Work Package 2

This report presents the findings from Work Package 2 of this Network Feasibility Study.

Since Work Package 1 indicated that a previous reinforcement project at a 132kV/11kV or 132kV/33kV substation should be considered in the case study, the work commenced with the selection of such a project. This is presented in Chapter 2.

To help the reader understand the problem that needs to be solved and the options available, Chapter 3 presents the conventional and superconducting solutions to the capacity problem of the chosen case. To further explore the impact of each solution in the electricity network, a number of power system studies have been completed in PSCAD which provided valuable learning on the electrical losses each solution produces, the expected power flows from each and the impact on the network fault levels.

Chapter 4 then uses all the learning presented in the previous Chapters to perform the Cost Benefit Analysis. This CBA provides a straightforward way to compare the two solutions and process all the information collected.

Chapter 6 explores the future of the superconducting cables and finally, Chapter 7, summarises the conclusions of this Work Package and presents the next steps in this network feasibility study.

7.2 Key Outputs and Next Steps

The case study of Work Package 2, considered the implementation of a superconducting solution to provide capacity to a 132/11kV substation that required reinforcement. As part of this work, detailed comparisons were performed between the superconducting and conventional solutions to investigate whether the superconducting implementation should be considered. The comprehensive descriptions of superconducting cable and XLPE cable are provided to give a full understanding each technology.

The main conclusions are:

- 11kV superconducting cables are capable of transferring power to substations requiring reinforcement in near future, by transferring the spare capacity from the nearby substations.
- Compared to conventional cables, 11 kV superconducting cable has advantages of delivering bulk power with one single cable, with reduced space or right of way, noise, losses (resulting in carbon emissions) etc.
- The present value of superconducting cable solution is £23.11m compared to £14.11m of conventional solution over the 40 years' operation. The

superconducting solution consisted of a superconducting cable providing one of the two infeed's to the substation while the second infeed was provided using the convention 132kV cable and 132/11kV transformer. The conventional solution consisted of two 132kV cables and two 132/11kV transformers providing the two infeed's to the substation.

- Superconducting cables are more suitable to be used, where conventional cables can't deliver due to space, noise or emission constraints, such as urban city and residential areas.
- Superconducting cables could be more cost effective to be used in heavily loaded areas over a short length.
- As pointed out in reference [5], superconducting cable cost can be significantly reduced in future. For the current study, if superconducting cable cost is reduced to £8/kA-m, then the present value of superconducting cable will be the same as conventional cable.
- The competitiveness of superconducting cable can be improved by reducing the cooling cost.

Overall, Work Package 2 of this network feasibility study has shown that superconducting solutions are currently significantly more expensive than traditional reinforcement solutions. For this reason, Work Package 3 will explore the future of superconducting cables and investigate in further detail the changes in the market and costs required to make them an attractive option for implementation in electricity distribution networks. Additionally, Work Package 3 will describe the unique case where Superconducting Cables could perhaps be the only reinforcement option in other DNO networks.

Appendix I

Temperature dependency of the superconducting properties

Mathematically, the temperature dependence of the critical current density of superconducting tapes is proposed by S. R. Curras and described using the Eq. A.1.

$$J_c(T) = \begin{cases} J_c(T_{ref}) \left(T_{ref} \frac{(T_c - T)^\alpha}{(T_c - T_{ref})^\alpha} \right) & \text{when } T_{ref} < T < T_c \\ 0 & \text{when } T > T_c \end{cases} \quad \text{Eq. A.1}$$

where α is 1.5 which is applicable to YBCO and Bi-2223 superconducting material. An operating temperature of 70 K is used as a reference temperature T_{ref} for the superconducting cable. $J_c(ref) = 3.5 \times 10^{10}$ A/m², and $T_c = 92$ K is the reference critical current density and critical temperature of the YBCO superconducting tape, respectively.

The resistivity of superconducting tape

For YBCO coated conductor, the YBCO superconducting layer will be in parallel with the copper stabilizer layer. If the current is less than the critical current value, the current flows through the superconducting layer because of zero resistance. However, the resistivity of the YBCO layer will exponentially increase when the current exceeds the critical current, which forces the majority of the current to be diverted into the copper stabilizer layer. Moreover, from Eq. A.1, the current density of the YBCO layer is 0 if the temperature is above the critical temperature level. Therefore, the resistivity of the YBCO superconducting tape can be mathematically considered as a piecewise function of applied current and temperature.

- (1) When the applied current I is less than the critical current I_c and the temperature of the HTS tape T is less than the critical temperature T_c , the superconductor is considered to be in the superconductive state. The resistivity $\rho_0 = 0$ describes this state.
- (2) When $I > I_c$ and $T < T_c$, the YBCO layer quenches, resulting in the exponential increase in resistance. This highly non-linear relationship of the superconductor between the current and the voltage is described using the E - J power law, and the resistivity of the superconductor can be calculated using Eq. A.2:

$$\rho_{HTS} = \frac{E_c}{J_c(T)} \left(\frac{J}{J_c(T)} \right)^{N-1} \quad \text{Eq. A.2}$$

where, $E_c = 1\mu\text{V}/\text{cm}$ is the critical electric field. The N value is usually between 21 and 30 for YBCO tapes. When the applied current is greater than the critical current, a joule heating effect occurs due to the exponential rise in ρ_{HTS} , leading to the rise in temperature of the superconducting material.

- (3) When $T > T_c$, the YBCO layer completely loses superconductivity and converts into a normal state. The applied current is then diverted into the copper stabilizer layer and again joule heating occurs in this copper layer, resulting in a dramatic rise in temperature. In this case, the resistivity of the superconductor is considered to be equal to the resistivity of the copper, which is a function of the temperature as expressed in Eq. A.3:

$$\rho_{cu} = (0.0084T - 0.4603) \times 10^{-8} \quad 77\text{ K} < T < 250\text{ K} \quad \text{Eq. A.3}$$

Heat transfer between the superconducting tape and the cryogenic envelope

The YBCO HTS tape has improved thermal conductivity thanks to the copper stabilizer layer. The heat exchange with an LN₂ cryogenic envelope is very efficient and the temperature difference of LN₂ along the axial direction of the cable depends on the almost negligible losses of the thermal leak; hence, the temperature of the LN₂ is maintained almost constant along the length of a cable of less than 1 km long. An example of this is illustrated by an 80 kV 500 m HTS cable demonstration project in KEPCO. The dissipated heating will be removed by pressurized flowing LN₂, resulting in a temperature difference of less than 3 K between the superconducting cable inlet and the outlet terminals. Hence, in the following thermal transfer analysis, only the temperature gradient in the cable transversal area is considered. The temperature of the 2G YBCO superconducting tape is considered as a piecewise function of the fault current.

- (1) When fault current occurs, $I > I_c$:

Based on the law of conservation of energy and assuming that there is no thermal exchange with the external environment, the heat generated by the superconductor is absorbed by the superconductor itself and the LN₂ envelope. The amount of heat that is absorbed by the superconductor results in an increase in the superconductor temperature while assuming that there is no temperature variation in the LN₂ envelope, since the duration of the fault current is quite small. The joule heating generated from the superconductor is expressed as Eq. A.4.

$$Q_{joule} = I^2rt \quad \text{Eq. A.4}$$

where, t is the time and r is the resistance of the superconductor, which can be obtained from the resistivity of superconductor ρ_s based on Eq. A.2 and Eq. A.3, the length l of the cable and area A of the superconductor in the transverse area. The resistance superconductor is expressed in Eq. A.5:

$$r = \rho_s \frac{l}{A} \quad \text{Eq. A.5}$$

The amount of heat (in joules) absorbed by the superconductor is calculated based on the heat capacity c and the mass m of the superconductor, as shown in Eq. A.6:

$$Q_{HTS} = cm\Delta T = cdAl(T_{n+1} - T_n) \quad \text{Eq. A.6}$$

where, d is the density of the superconductor, and ΔT is the temperature increment, expressed as $T_{n+1} - T_n$ in each iteration step. The heat exchange rate represents the cooling ability and is described by the heat transfer coefficient h . There is currently no analytical expression for h to represent the efficiency of removing the dissipated heating from superconductor to cryogenic envelope. But in general, an empirical formula can be used, as in Eq. A.7:

$$h = \alpha\Delta T^\beta + k \quad \text{Eq. A.7}$$

where the parameters α , β and k are dependent on the temperature variation interval. The amount of heat in joules generated from the superconductor, which can be removed by the LN₂ cryogenic envelope, is calculated as Eq. A.8:

$$Q_{LN2} = 2hwlt(T_{n+1} - T_{in}) \quad \text{Eq. A.8}$$

where w is the width of the superconductor, $2wl$ is the total area of the wide face of the HTS tape and $T_{in} = 70$ K is the temperature of LN₂. The area of the transverse face is ignored due to the high aspect ratio of the 2G YBCO HTS tape. Assuming there is no heat leakage, the thermal equilibrium equations can be obtained as expressed in Eq. A.9:

$$Q_{HTS} = Q_{joule} + Q_{LN2} \quad \text{Eq. A.9}$$

The temperature of superconductor T_{n+1} is updated at each calculation iteration over a time interval ΔT and can be calculated based on Eq. A.4 to Eq. A.9 with some substitutions, as expressed in Eq. A.10:

$$T_{n+1} = \frac{Q_{joule} + cdAlT_n - 2T_{in}hwlt}{cdAl - 2hwlt} \quad \text{Eq. A.10}$$

(2) When the fault current finishes, $I < I_c$:

The fault current ends and the superconductor starts to convert from the normal state to the superconductive state, only if it is not permanently damaged. The previously generated heat is continuously removed by LN₂ and the temperature of the

superconductor gradually decreases back to operating temperature, as expressed in Eq. A.11:

$$T_{n+1} = \frac{cdAlT_n - 2T_{in}hwlt}{cdAl - 2hwlt} \quad \text{Eq. A.11}$$

The parameters used in Eq. A.4 to Eq. A.11 are summarized in Table A.1. It should be noted that the density of the YBCO superconducting layer is approximately equal to the density of the copper. As the copper stabilizer is much thicker than the rest of the layers, the mass of the copper dominates.

Table A.1: Values of parameters used in Eq. A.4 to Eq. A.11.

Parameters	Values
Width of the YBCO tape (w)	0.004 m
Transverse area of the YBCO tape (A)	$4 \times 10^{-9} \text{ m}^2$
Length of the cable (l)	5 km (unit length)
Thermal capacity of YBCO (c)	200 J/kg · K
Density of the YBCO tape (d)	$8.8 \times 10^3 \text{ kg/m}^3$

Appendix II

Present Value calculation

The two basic concepts of present value (PV) are:

- i. that all benefits and costs are calculated in terms of today's dollars (that is, present value) and
- ii. that benefits and costs are combined to give a net value

The first step in calculating the NPV is to decide on the discount rate to use. The discount rate equates future values to current values. For example, £100 received one year in the future is only worth £94.34 today with a discount rate of 0.06 (6 percent). The equation that represents this is:

$$present\ value = \frac{amount\ received\ in\ future}{(1 + discount\ interest\ rate)^{number\ of\ years}} \quad Eq.\ B.1$$

For amounts received more than one year in the future—for example, in three years—the discount rate is applied three times to give a discount factor. Let's use PV for present value, FV for future value, *i* for discount interest rate, *F* for discount factor, and *n* for the number of years in the future. The equations that apply to find a present value for a future value across multiple years are:

$$F_n = \frac{1}{(1 + i)^n} \quad and \quad PV = FV \times F_n \quad Eq.\ B.2$$

For example, £100 received three years hence at a discount rate of 6 percent is:

$$F_n = \frac{1}{(1 + 0.06)^3} = 0.8396 \quad Eq.\ B.3$$

$$PV = £100.00 \times 0.8396 = £ 83.96 \quad Eq.\ B.4$$

Finance books provide tables of discount factors by discount rate for multiple years, so you do not have to calculate them. Table B-1 shows the table containing the NPV calculations that were done for WPD, as presented in Chapter 3. Notice that the NPV calculation is done over a period of 10 years (for cable operation). In the Table B.1 and B.2, first three years are considered as installation years, during which no losses occur. While the rest of the 10 operating years contribute to losses. The losses are termed as ongoing costs, which are assumed to be constant and calculated based on modelling result and a cost factor of £48/MWh. The anticipated benefits are also associated with the year in which they accrue. But for this project they are considered as zero, as there is no sufficient information and also it is the same for solutions, hence doesn't affect the solution at all.

Table B.1: Present Value Calculation of the Conventional solution for 10 years, considering average load

	Installation Year 1	Installation Year 2	Installation Year 3	Operating Year 1	Operating Year 2	Operating Year 3	Operating Year 4	Operating Year 5	Operating Year 6	Operating Year 7	Operating Year 8	Operating Year 9	Operating Year 10
Capital cost	5,425,099	5,425,099	2,712,549	-	-	-	-	-	-	-	-	-	-
Discount rate	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Value of Benefits	-	-	-	0	0	0	0	0	0	0	0	0	0
PV of Benefits	-	-	-	0	0	0	0	0	0	0	0	0	0
Ongoing and Operating Costs	-	-	-	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88	44,570.88
PV of costs (w.r.t. mid-year)	-	-	-	39,514.82	38,178.57	36,887.51	35,640.10	34,434.88	33,270.42	32,145.33	31,058.29	30,008.01	28,993.25
NPV (by year)	5,425,099	5,241,642	2,532,194	39,514.82	38,178.57	36,887.51	35,640.10	34,434.88	33,270.42	32,145.33	31,058.29	30,008.01	28,993.25
Cumulative NPV	5,425,099	10,666,742	13,198,936	13,238,451	13,276,629	13,313,517	13,349,157	13,383,592	13,416,862	13,449,007	13,480,066	13,510,074	13,539,067

Table B.2: Present Value Calculation of the Superconducting solution for 10 years, considering average load

	Installation Year 1	Installation Year 2	Installation Year 3	Operating Year 1	Operating Year 2	Operating Year 3	Operating Year 4	Operating Year 5	Operating Year 6	Operating Year 7	Operating Year 8	Operating Year 9	Operating Year 10
Capital cost	9339785.01	9339785.01	4669892.51	-	-	-	-	-	-	-	-	-	-
Discount rate	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%	3.50%
Value of Benefits	-	-	-	0	0	0	0	0	0	0	0	0	0
PV of Benefits	-	-	-	0	0	0	0	0	0	0	0	0	0
Ongoing and Operating Costs	-	-	-	33992.63	33992.63	33992.63	33992.63	33992.63	33992.63	33992.63	33992.63	33992.63	33992.63
PV of costs (w.r.t. mid-year)	-	-	-	31,018.28	29,828.54	28,638.79	27,449.05	26,259.31	23,879.83	22,690.08	21,500.34	20,310.60	19,120.86
NPV (by year)	9,339,785	9,023,947	4,359,395	30,136.55	29,117.44	28,132.80	27,181.45	26,262.27	25,374.17	24,516.11	23,687.06	22,886.05	22,112.12
Cumulative NPV	9,339,785	18,363,732	22,723,127	22,753,263	22,782,381	22,810,513	22,837,695	22,863,957	22,889,331	22,913,847	22,937,534	22,960,420	22,982,533



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