Economic Analysis of Interconnecting Distribution Substations via Superconducting Cables

Chenghong Gu, *Student Member, IEEE*, Yan Zhang, *Student Member, IEEE*, and Furong Li, *Senior Member, IEEE*, and Weijia Yuan

***Abstract*—This paper presents an preliminary study of using superconducting cables to interconnect two distribution substations in urban areas in distribution networks. To compare the approach with the conventional underground cables, discussion and calculation is carried out in terms of factors that affect the interconnection: investment cost, reliability, energy loss, capacity, environmental impact and the impact to the fault current limit. A test system is utilized to demonstrate the study. The main findings are: i) superconducting cables are more suitable for transferring large amount of electricity over long distance regarding of costs, capacity and energy losses; ii) superconducting cables can compete with conventional cables when operating over long time span; and iii) the reliability of superconducting cables needs to be improved in order to promote their practical application.**

***Index Terms*— Superconducting cable, Substation interconnection, Investment cost, Reliability**

I. Introduction

DRIVEN by environmental objectives set at both EU and national level, the electricity demand in the UK is expected to be more than twice of its current figure by 2050, which will mainly be driven by electrification of heating and transportation [1]. As seen in Fig.1, the system peak demand in the UK is 123.3 GW compared that without electric vehicles (EVs) and heat pumps (HPs) in 2050. The UK government has set an ambitious target to reduce greenhouse gas emission: it aims to reduce the emission by 80% by 2050 compared to 1990 level. This decarbonization process is accompanied by a series of initiatives that the government is taking in promoting renewables, energy efficiency and demand reduction. As a result, the UK power sector is expecting significant shifts in the nature, size and location of future generation and demand. Since a large amount of clean appliances are expected to connect to lower voltage distribution networks, this decarbonization shift would require substantial network investment particularly in distribution networks. The size of the investment is greatly dependent on the nature and location of future generation and demand [2].

The authors are with the Department of Electronic and Electrical Engineering, University of Bath, Bath BA2 7AY, U.K. (e-mail: cg277@bath.ac.uk; yz248@bath.ac.uk; f.li@bath.ac.uk; wy255@bath.ac.uk).

Currently, the major of substations in the distribution networks are still planned in a radial manner. In order to maintain network security mandated by system planning and operation security standards [3], most of transformers are not fully loaded, reserving large volume of spare capacity for network emergency. It is therefore quite attractive and economical to interconnect the existing substations that closely located. The benefits of interconnection can be identified in the following aspects: i) increasing the use of the spare capacity of existing transformers, ii) improving the reliability of energy supply, iii) reducing or deferring the need for network investment, and iv) providing flexibility to network operators [4].

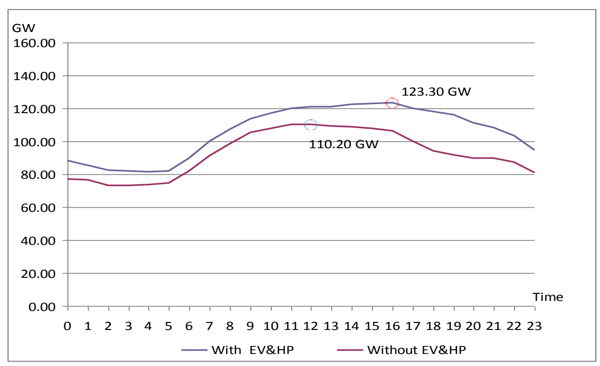

Fig.1. a typical predicted UK demand from file in 2050

The typical way to interconnect two substations is via traditional underground cables, but one obvious disadvantage with this approach is that the cables capability is limited. Another way is through superconducting cables which is a newly emerging technology towing to the recent development in superconductor materials and reduction in costs.

Compared to other types of conductors, superconducting cables can carry a significantly larger current density and require a drastically lower cooling cost. Recently massive manufacture of high-temperature superconducting (HTS) materials has enabled superconductivity to become a preferred candidate to help generation and transportation of clean energy. A number of industrial prototype superconducting devices have been investigated and tested and they are now on the edge of large scale electrical power applications. HTS are able to carry a significantly larger current density and sustain a significantly larger magnetic field, thus they are very attractive for electrical power applications. Besides, their prices keep decreasing and the projected prices in future are acceptable for power industries.

HTS power transmission cables present an attractive alternative to conventional copper cables, offering a significantly higher efficiency and transmission capability with reduced requirement on right-of-way. They are a preferred technology to link rapid-expansion grids and connect growing remote renewable energy generation. In the past decade, a number of prototype 2G HTS cables have been investigated and tested in real grids. The Department of Energy supported several superconducting cable projects including Albany and LIPA cable [5]. A 5GW DC superconducting network project was proposed to interconnect three major US grids[6] . Danish Energy of Agency supported a high-temperature superconducting cable project which was in operation from 2001 to 2003 [7]. Another promising application of superconducting cables is interconnecting substations in urban areas and delivering DC power over a long distance.

This paper conducts a detailed comparison between conventional cables and HTS cables for interconnecting two distribution substations, in terms of cost, reliability, energy loss, capacity, and environment impact to fault current limit. It demonstrates the comparison on two typical substations taken from the UK network.

The rest of this paper is organized as follows: Section II discusses the advantages of interconnecting substations and introduces the characteristics of superconducting cables. Section III provides an analysis to the comparison between superconducting cables and conventional underground cables from several aspects. A simple demonstration to is carried out in Section IV. Conclusions are drawn in Section V.

II. Interconnection of Substations

A. Advantages of Interconnecting Substations

Substations are the main facilities to distribute electricity to end customers. Due to their capacity limits and insulation issues, transformers can only be run overloaded for a certain period of time and longer time overloading is not allowed. They should be reinforced or replaced with larger capacity ones if their capacity is on longer able accommodate the growing demand. The expansion of existing substations or construction of new substations might not be an economical choice due to a couple of constraints.

i) Space: there is limited or no space available for expansion or constructing new substations; it is often the case in heavily populated urban areas;
ii) Costs: the investment in obtaining enough space for sites, the costs of civil engineering and materials could be extremely high;
iii) Environmental impact: the leakage magnetic field produced by substations might be raised as a safety and health issue to the public;
iv) Others: there is a risk that the investment might be too early or on a too large scale and huge loss could be incurred if the demand growth is not coming as previously predicted.

Due to these issues, network operators are not willing to risk overinvestment in constructing new substations, but rather turn to other techniques to improve the loadable capability of the existing facilities. An attractive alternative is to closely interconnect the existing substations that are not fully loaded. The major benefits of interconnecting substations at lower-voltage side buses are

i) increasing use of spare capacity by equalizing/balancing the loading among different substations;
ii) improving network reliability by transferring the load supported by the failed substation to the working ones;
iii) reducing or deferring the need for network investment by increasing loadable capability of the existing substations;
iv) providing flexibility to network operators to manage voltage and power flows.

B. Superconducting Cables

HTS materials can be made into cables for connection of substations. Liquid nitrogen can be used as a coolant to maintain an operation temperature between 65K and 77K. Normally, the cable system consists of four main parts: HTS cables, cable end terminations, a cooling system and a monitoring system. The configuration of an example superconducting cable is show in Fig.2 [8].

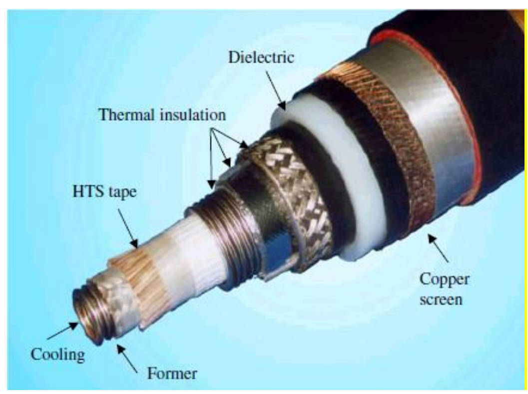

Fig.2. Superconducting cable design

Compared to conventional copper cables, there are a number of advantages provided by superconducting cables: i) the engineering current density is about 100 times more than a copper cable at the proposed temperature 65K-77K [9]; ii) the energy loss of a superconducting cable is significantly lower than a conventional copper cable; iii) a superconducting cable is able to act as a fault current limiter therefore effectively increasing system reliability; iv) there is no electromagnetic field pollution; and v) the inductance is low.

III. Advantages of Superconducting Cables

This section explains the six major aspects with superconducting cables in details to interconnect substations.

A. Cost

So far the unit price of a HTS conductor is still very high compared to conventional copper. For the first-generation HTS conductor, the cost is mainly coming from the material silver, whereas the cost for the second-generation HTS conductor mainly comes from the manufacturing process. For HTS material, the market price now is about $100-200/kA*m; while for copper the price is about $40/kA*m. For a superconducting cable, half cost is coming from 2G HTS materials. Only around 5%-10% of the cost is coming from the cooling system.

B. Reliability

Three factors need to be considered for estimation reliability of a superconducting cable: superconductor, insulation and cooling systems. If no external force is applied, superconducting cables will maintain their characteristics permanently. Since the temperature is maintained at a constant value within a superconducting cable, there are no factors that can lead to deterioration, and thus a long-term stable operation can be achieved. Liquid nitrogen is a nature insulator. A study shows that an insulation material used for conventional cables can also be used at low temperatures [9]. A life in excess of 30 years is estimated for the insulation material and according to manufacturers for cooling systems, a continuous operation in excess of more than 5000 hours is expected. The maintenance interval for the cooling system is recommended to be one year.

Although there are a number of demonstration projects across the world, there is no statistical data for failure rates or maintenance hours for superconducting cables. In the Long Island Power Authority superconducting cable project, there were several conditions in which the cables were taken offline during a two-year in-grid operation [10]. In a Korea Electric Power Corporation superconducting cable project, a continuous 30 day in grid test was achieved without any failures or interruptions [11]. In a project supported by Danish Energy Agency, a superconducting cable was in operation connected with a grid from 2001 and 2003, but there were 14 faults in the operation period [7].

C. Energy Loss

One of the major advantages of superconducting cables is that they have quite low energy loss over the traditional cables. For an AC superconducting cable, the energy losses come from AC loss that is comparable to the magnetization loss, the dielectric loss of the insulation and the heat loss via thermal insulation. Liquid nitrogen is used to compensate the energy loss to maintain desirable operation temperature. Its efficiency at 77K is about 10%. Typically, the energy loss of an AC superconducting cable is between 3-4% [9], while for a conventional cable it is around 8%. For a DC superconducting cable, the energy loss only comes from the dielectric loss and heat low, which is estimated to be only about 1-2% [12].

D. Capacity

The superconducting layer is able to carry a current density one million times of that of a copper. Made into an engineering conductor, a superconductor is able to carry a current density of over 100 A/mm^2, which is more than 100 times of that of a copper cable [9]. According to Korea Electric Power Corporation, superconducting cables can be placed strategically in urban power grids to deliver up to 10 times more power than conventional cables in the same right-of-way to mitigate grid congestion or can be used to replace traditional overhead lines.

E. Environmental Impact

Unlike conventional cables, there is no leakage magnetic field produced by a superconducting cable, thus EMF pollution is eliminated. This is because there is a shielding layer made for superconductors in the cable design. This shielding layer is able to constrain the magnetic flux within the cable duct. In addition, HTS cables do not require any thermal de-rating.

F. Fault Current Limiting

A superconducting cable is able to address excessive fault current challenges naturally due to its own properties. It can be designed in such a way that it is fault current limiting, hence improving the grid stability and eliminating the need for upgrading protection equipment.

IV. Example Demonstration

This section compares the costs, reliability and efficiency of using traditional cables and HTS cables to interconnect two practical substations taken from the UK system in Fig. 3. In the system, each substation has two parallel transformers and the distance between the two substations is 2 km. The data of the two substations is given in Table I.

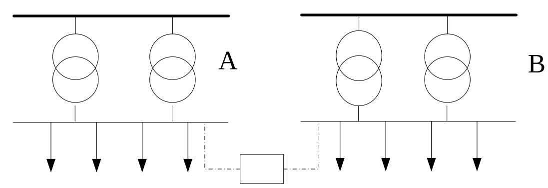

Fig.3. Interconnecting of two substations

TABLE I
SUBSTATION DATA

	Capacity (MVA)	Demand (MVA)	Transformer Unit Cost (£k)
Substation A	70×2	82	990
Substation B	70×2	60	990

The used underground cable has a typical rating of 20MVA and a unit cost of £250k/km. Its reliability parameters are assumed to be: failure rate 0.1time/year, mean time to repair: 10 hour/time [13]. For the same voltage level superconducting cable, its capacity is supposed to be 10 times of the traditional cable, i.e. 200MVA and its unit cost is £1million/km. Due to the scarcity of the available data, the failure rate and mean time to repair of a cable is assumed 4 times of the traditional cables to consider its more complex composition.

The load growth rate is chosen as 2.2%, the averagely projected rate in the UK over the next 40 years, where both EVs and HPs are included.

A. Cost Comparison

The system is developed to accommodate the demand increase with a reliability level of being able to withstand N-1 contingencies. The investment costs are summarized in table II.

TABLE II
INVESTMENT AND THE COST COMPARISON OF THE INTERCONNECTOR

Underground cable	Cable 1 in 2010	Cable 2 in 2014	Cable 3 in 2027	£1500 k
HTS cable	Cable 1 in 2010	No	No	£3000 k

Two transformers need to be reinforced in order to accommodate the demand by 2050, whatever the two substations are interconnected by conventional cables or HTS cables. If the two substations are interconnected with conventional cables in 2010, one extra cable should be constructed in 2014 and the third one should be built in 2027 in order to be able to accommodate the demand growth. They totally cost £1500k (the same inflation rate and discount rate used; other factors influencing the material costs not considered). If the two substations are interconnected via a superconducting cable, only one is needed in 2010, and there is no further investment in interconnection cable required. The cost is to build the HTS cables, counted as £3000k. By comparison, HTS cables are not comparable with conventional cables in terms of investment costs.

B. Reliability Comparison

To simplify analysis, this study investigates the system reliability in three selected years 2010, 2020, and 2050 with the new investment included.

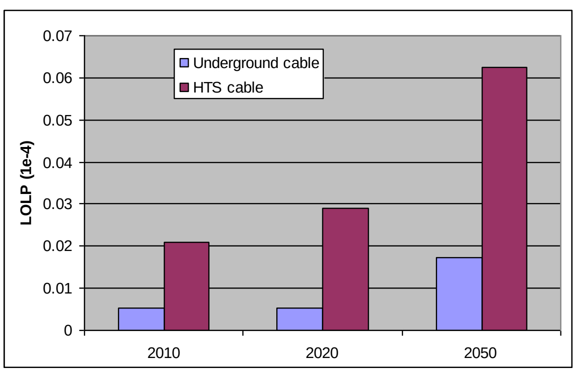

Fig.4. Comparison of LOLP

Fig.4 shows that with the demand growth, the system Loss of Load Probability (LOLP) increases accordingly, whatever the interconnector is underground cables or HTS cables. By contracts, the underground cable interconnector produces smaller LOLP because its higher reliability level. Another reason is that more parallel cables are constructed in the system and they can reduce the probability of system failure. By contrast, only one HTS cable is in operation and it is less reliable compared to traditional cables and its failure will disconnect the two substations, leading to a less reliable system.

Similarly, in terms of Expected Energy Not Supplied (EENS), conventional cables have greater reliability than HTS cable, but the difference between the two techniques is reduced because that the HTS cables have great capacity to transport energy. The small capacity of the conventional cables limits their transfer capability. For example in 2020, if the two transformers in substation A both go offline, the HTS cables can transfer 100MVA energy to the customers connected at substations A, but the conventional cables can only transport 40MVA.

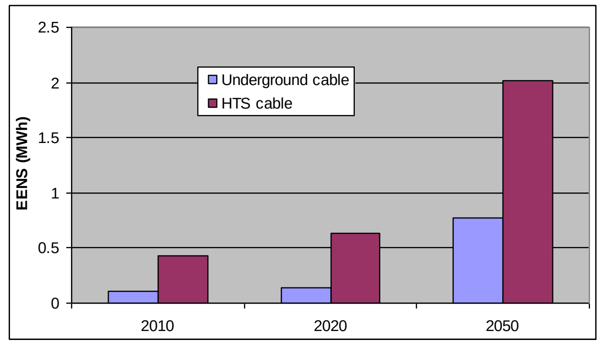

Fig.5. Comparison of EENS

Overall, in terms of reliability, conventional cables overwhelm HTS cables but the HTS still competitive if reliability is not major concerns.

C. Energy Loss and Efficiency Comparison

Fig.6 compares the energy loss along the interconnectors with the two different interconnecting technologies from 2010-2050 under different levels of system average demand to the peak demand.

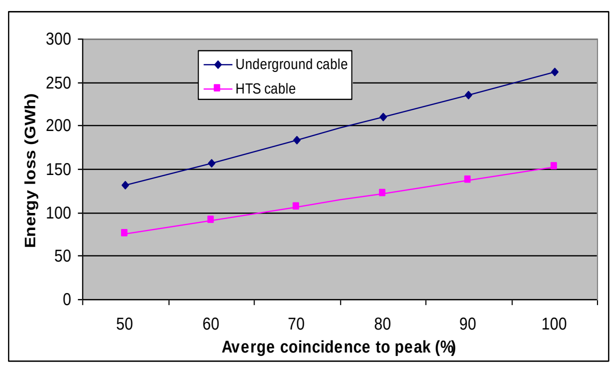

Fig.6. Comparison of energy loss

From this aspect, HTS cable is very competitive. Its energy loss is around half of that produced by the traditional underground cables at all levels. The benefit increases even high when the system loading level rises. Therefore for HTS cables, if operated for long period, the savings from energy loss might be able to compensate the investment costs.

V. CONCLUSION

This paper has presented the recent development in superconducting cables and used it to interconnect two urban distribution substations. The technique is compared with the conventional cables. From the study, the following conclusions are reached:

i) Superconducting cables are promising in promoting the transmission capability of the existing networks. They have less environmental impact, larger transmission capability and lower energy loss.
ii) Compared with traditional cables, superconducting cables are not competitive in construction costs, which are 5-10 times higher. But, superconducting cables have great efficiency in reducing network loss, especially for long-term operation.
iii) The reliability of superconducting cables is as not as high as traditional cables due to the complexity of the cooling systems, but they are still acceptable if reliability is not a big concern.

Superconducting cables are very suitable for transferring large amount of power flows over long distances. If their reliability can be improved and costs can be further reduced in the future, they can replace conventional underground cables in certain circumstances to be used efficiently, economically, and environment-friendly.

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VII. Biographies

Chenghong Gu (S'09) was born in Anhui province, China. He received his Master degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2007. In 2010, he received his Ph.D. in Electrical Engineering from University of Bath, U.K. His major research is in the area of power system economics and planning.

Yan Zhang (S'10) was born in Shaanxi province, China. She received her Bachelor and Master degrees in Electrical Engineering from North China Electric Power University, Beijing, China, in 2005 and 2008 respectively. Now, she is a PhD student with University of Bath, U.K. Her major research is in the area of power system pricing and planning.

Furong Li (M'00, SM'09) was born in Shannxi province, China. She received the B.Eng. degree in electrical engineering from Hohai University, Nanjing, China, in 1990 and the Ph.D. degree from Liverpool John Moores University, Liverpool, U.K., in 1997. She then took up a lectureship with Department of Electronic & Electrical Engineering, University of Bath, where she is a Professor in the Power and Energy Systems Group. Her major research interest is in the area of power system planning, analysis, and power system economics.

Weijia Yuan was born in China. He received the bachelor degree in electrical engineering from Tsinghua University China and the Ph.D. degree from University of Cambridge, UK. He joined the University of Bath as a lecturer from 2011. His major research interest is in the area of electrical power applications of superconductivity.