Review of the Conceptual Design for the Use of HTS Power Transmission Cable for a Metropolitan Area

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Abstract - The necessity of compact high temperature superconducting cables is more keenly felt in densely populated metropolitan areas. Because the compact high-temperature superconducting cables can be installed in ducts and tunnels, thereby reducing construction costs and making the use of underground space more effective, the effect of introducing it to the power system will be huge. Seoul, Korea, is selected as a review model for this paper. The loads are estimated by scenario based on a survey and analysis of 345kV and 154kV power supply networks in this area. Based on this, the following elements for an urban transmission system are examined. (1) A method of constructing a model system to introduce high-temperature superconducting cables to metropolitan areas is presented. (2) A case study is conducted through the analysis of power demand scenarios, and the amount of high-temperature superconducting cable to be introduced by scenario is examined. (3) The economy involved in expanding existing cables and introducing high- temperature superconducting cables(ducts or tunnels) following load increase in urban areas is examined and compared., and standards for current cable ducts are calculated. (4) The voltage level that can be accommodated by existing ducts is examined.

Keywords: superconducting power cable, duct, tunnel, transmission capacity, voltage class, system modeling

1. Introduction

The demands for electric power are expected to rise with the recent trend of large cities becoming increasingly information and intelligence oriented. Particularly in Korea, the demands for power have steadily increased every year. The demands for power are estimated to increase to 425,600GWH in 2020, 1.7 times the current level[1,2]. Due to aesthetics and the difficulty in securing aboveground space, mostly underground transmission lines are used for the downtown areas of large cities worldwide. Accordingly, more attention is given to the construction of underground transmission lines to secure urban power supply. However, as the underground spaces in large cities are already overcrowded with subway, communication, water supply, and building facilities, the construction of ducts and tunnels for transmission lines is expected to be very difficult. Moreover, current underground cable construction costs consist mostly of engineering work, such as the construction of ducts. Since the cost of engineering work is expected to rise with time, the power transmission cost will rise also. To reduce the power transmission cost, the issue of retrofitting existing ducts with compact large capacity transmission cables has been raised. Since high- temperature superconductor can maintain superconductivity with relatively low-cost liquid nitrogen as well as carry 1,000 times the current per unit wire space (critical current density) of room-temperature conductors, such as copper, constructing large capacity compact cables is possible using HTS. Such a need for compact HTS cable is felt most keenly in densely populated metropolitan areas. The impact of its application in the power grid is estimated to be tremendous as construction cost will be reduced and underground space will be used more effectively. For these reasons, active research on compact HTS cables is underway in Japan and other countries[3,4]. However, these studies cannot be applied globally, since the load and system characteristics are different in each country. In other words, when the possibility of applying HTS cable is examined, the voltage class, transmission capacity, and model to be applied need to be carefully examined based on the special characteristics of each country, and the same is true for the evaluation of its market size and economy. Based on this rationale, to examine the effect of the application of HTS cable, the author evaluated the economy of applying sections of HTS cable in Seoul, Korea [5]. To increase the effect of the application of HTS cable, the voltage class applicable to existing ducts, suitable transmission capacity, and power grid configuration in large cities are examined

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in this study. The market size with the high-capacity high-density transmission lines using HTS cable applied based on the future power demand scenario [6] is estimated by year, and the economies of traditional cable and HTS cable are compared and evaluated according to the latter's market share. For a specific case study, Seoul, Korea, is selected as an examination model and the concept design is examined.

2. Main Discourse

2.1 Standards for current cable duct design

The standards for the design of the inner diameter of underground ducts used in Korea by underground cable type and installation method are as follows. The inner diameter of the duct is determined by considering maximum external diameter of the cable, future capacity increase, and economy. Here, D is the inner diameter of duct(mm) and d is the maximum external diameter of cable(mm)

(1) The 1 hole 1 cable installation has to simultaneously satisfy both of the following formulas.
$D \geq 1.3d$, $D \geq d + 30mm$

(2) The 1 hole 3 cable installation has to satisfy the following formula.
$2.16d + 30mm \leq D \leq 2.85d$ or $D \geq 3.15d$ In other words, a duct whose inner diameter $2.85d \leq D \leq 3.15d$ is inappropriate.

The standard inner diameter of the duct by cable type is shown in Table 1.

Table 1 Standard inner diameter of duct by cable type

Cable type	Conductor size	Inlet method	Inner diameter of duct	Note
66kV single core XLPE Ca-	400mm^2	1hole 1cable	100mm	OF:Oil Filled Cable XLPE:Cross-linked Poly-ethylene cable
154kV single core OF Cable	Under 2,000mm^2	1hole 1cable	200mm	
		1hole 3cable	300mm	
154kV single core XLPE Cable	Under 1,200mm^2	1hole 1cable	200mm	
		1hole 3cable	300mm	
	Under 2,000mm^2	1hole `1cable	200mm	

According to the above design standards, if an HTS cable is to be put into an existing duct of 200mmΦ, the maximum external diameter of cable needs to be 153mm.

2.2 Model system for the application of an HTS cable system

Generally, temperature rise limits the current capacity of underground cable. If this limitation can be alleviated using an HTS, the current capacity can be increased. Therefore, it is possible to transmit 1GW class large capacity through 154kV class low voltage instead of high voltage. Fig 1 shows the cross-section of each cable when 1GW is transmitted. The cable shown in the upper part of Fig 1 is the superconducting metallic cable cooled with liquid helium, which also needs a nitrogen shield outside the liquid helium for thermal insulation. The liquid nitrogen cooled cable using HTS, shown in the middle of the figure, can be considerably more compact because it does not need two-layer thermal insulation. Accordingly, it can replace the underground cable installed in the current duct and increase current capacity considerably. When compared with the XLPE cable carrying the same amount of power shown in the lower part of the figure, the HTS cable's compactness is clear. As the construction cost of the duct and tunnel that encase the cable accounts for a large part of total construction cost, the advantage of compactness is very large. Metropolitan areas in Korea have formed high-capacity, high-density power consumption areas accompanying the development of information society. To provide reliable power supply to these areas, the power grids of large cities consist of the following. A 345kV outer line is constructed surrounding a metropolitan area, and several base substations on the outer line collect large power transmitted through 345kV overhead transmission lines from faraway thermal power plants or nuclear power plants. Overhead transmission lines and underground cables connected to these base substations on the outer line or coastal thermal power plants in suburban areas are installed toward the center of city.

This paper examined a model system for the application of HTS cable to metropolitan area power system. The current density of a HTS cable is 106A/cm^2. A model system in which a traditional cable system and HTS cable are applied is shown in Fig 2. The system drawing in the upper part of Fig 2 shows a general supply network of traditional cables in large cities. In the system using traditional cable, part of 765kV or 345kV transmitted from power plants is reduced to 154kV at 345/154kV substations located at outskirts of the city and is carried to ducts or tunnels and the rest is reduced to the distribution class of 22.9kV at 154/22.9kV distribution substations in the cities and is carried to ducts or tunnels. The system drawing in the lower part of Fig 2 shows the supply network of HTS cables. In the system using HTS cable, electric power transmitted from power plants is reduced at 345kV/154kV substations and is carried to ducts equipped with refrigeration system. Since no tunnel construction is required, the construction cost can be reduced substantially.

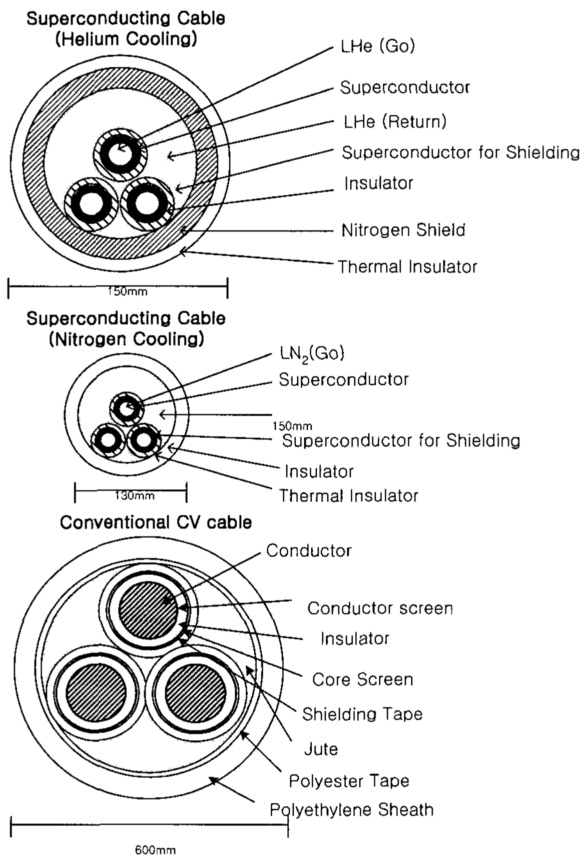

Fig. 1 Cross-section of various cable when 1GW capacity is transmitted

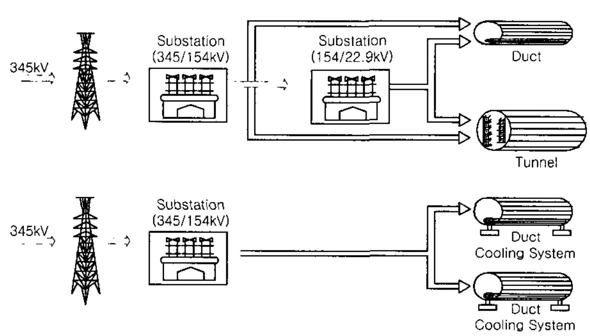

Fig. 2 Model system configuration to apply superconducting cable to a metropolitan area

2.2.1 Conceptual design of compact HTS cable

1) Examination of cable transmission capacity

In Korea, 345kV substations are located in a loop in the city outskirts. From these substations, 320MW power is transmitted through 154kV substations in the downtown area. When we assume the rate of power demand increase to be 3.0% a year, three times the current capacity will need to be transmitted in 30 years. But the underground space in large cities is already overcrowded with subway, gas, water, and communication facilities.Therefore, securing additional cable ducts or tunnels to cope with this load increase will be very difficult, both technically and economically, in the future. In addition, it will be very difficult to install GW class normal conductor cables and metal superconducting cables in the existing ducts and tunnels without introducing special engineering for cooling and thermal insulation from heating and design aspects. When the HTS is utilized as cable material, the external diameter of the cable can be reduced compared to the existing room-temperature cable or metal superconducting cables because HTS cables generate almost no heat and the insulation layer can be designed compactly. When this is realized, HTS cables using existing ducts or tunnels can replace the current regular cables.

In general, power is supplied through a double route cable system in large cities in consideration of system reliability. In Korea, in the case of 154kV, typically a route carries 330MW. When the annual power demand increase is assumed to average 3.0%, the increase per route will be about 800 MW in 30 years. Considering the demand estimation is typically 20-30 years maximum, power transmission of 1 GW per route at the maximum will be suitable in the future. Therefore, to transmit power of this capacity using 400kV XLPE cable under development, the external diameter of the cable must be 365mm, which will be difficult to accommodate with existing 200mmΦ ducts. Thus, securing new routes is necessary.

As discussed above, when compact cables using the HTS are developed, they can be used to retrofit existing ducts and tunnels to deal with transmission capacity increase following load increase that cannot be handled by traditional cables. It will, in turn, decrease cost and render use of underground space more effective.

2) Examination of cable system voltage

As the model system is based on the premise of using HTS cables in the existing ducts, the cable system voltage must be determined in consideration of this. In other words, if voltage is decreased, the insulation layer will be thinner but the current will increase and the AC loss will increase., Thus, the diameter of the refrigerant pipe must be increased to compensate. On the other hand, if the voltage is increased, the diameter of the refrigerant pipe will decrease but the insulation layer will increase. In short, the factors deciding the diameter of the superconducting cable can be summarized as follows.

- From the cooling aspect, the lower the voltage, the more current needs to be transmitted, and the insulation pipe grows due to an increase in AC loss.

- From the insulation aspect, the lower the voltage, the smaller the external diameter of cable.

Therefore, for the transmission capacity of 1 GW, the external diameter of cable is 130mmΦ, at 66kV and 150mmΦ at 154kV. Both can be accommodated by existing ducts of 200mmΦ. The current density(Jc) needed here is 1×10^6A/cm^2. Based on the examination above and in consideration of the existence of 154kV in the existing system voltage class, 154kV is most appropriate for the cable voltage class.

2.2.2 Estimation of the market size of HTS cable

In the U.S.A, Europe, and Japan, the application of transmission lines using HTS cables in the future power transmission system is being actively examined. To achieve this implementation, a lot of effort has been put into the system application technology of compact HTS cable to increase cable transmission capacity and to reduce underground construction cost. The size of this HTS cable market will be the size of the existing 154kV and 345kV market it will replace. To estimate the market size of HTS cable by voltage class of existing 154kV and 345kV, the following assumptions are made.

- The base year of the introduction of HTS cable in the market will be 2008.
- The market share will increase by 3.4% a year.(based on the S-Curve, which is referred to by the U.S. Department of Energy)
- The estimation of power demand increase is based on the fifth mid-long-term power demand estimates by the Ministry of Commerce, Industry, and Energy.

To estimate the market size of HTS cable by voltage class based on these assumptions, the data of 154kV and 345kV cable line lengths for five years(1995 to 1999) and the annual power demand estimated by the Ministry of Commerce, Industry, and Energy are shown in Tables 2 and 3. Table 4, shows the unit construction costs of 345kV and 154kV cables based on itemized statement of KEPCO's investment in unit cost in 2000."

When we examine the past trend provided in Table 2, the lengths of 154kV and 345kV cable lines used were 1,299c-km and 93c-km, respectively, in 2000. The total power sold was 239,500GWH. The rates of underground transmission line by voltage according to power demand are 5.42[c-m/GWH] and 0.39[c-m/GWH] respectively. Based on this, the annual market share of superconducting cable, the power demand estimates of Table 3, and the itemized statement of investment in unit cost provided in Table 4, the cable lengths of superconducting cables by voltage class of 154kV and 345kV are estimated by using Formula(1) and Formula(2).

Table 2 Trend of underground power line use for five years

Category / Voltage	Line length by year [c-km]				
	1996	1997	1998	1999	2000
345kV	-	49	71	93	93
154kV	822	943	1,055	1,112	1,299
Total	822	992	1,126	1,205	1,392

Table 3 Mid-long-term power demand estimate[GWH]

Year		Power demand estimate
2002		250,000
2003		264,000
2004		278,800
2005		294,700
2006		303,800
2007		313,300
2008		323,000
2009		333,000
2010		343,200
2011		350,700
2012		358,300
2013		366,200
2014		374,100
2015		381,800
2016		390,100
2017		398,800
2018		407,500
2019		416,500
2020		425,600
Average annual increase (%)	'2002 ~ '2005	5.6
	'2006 ~ '2010	3.1
	'2011 ~ '2015	2.2
	'2016 ~ '2020	2.2

Line length of 154kV underground cable[c-m] = 5.42 [c-m/GWH] × Annual power demand estimate[GWH]-----(1)

Line length of 345kV underground cable [c-m] = 0.39 [c-m/GWH]×Annual power demand estimate[GWH]------(2)

Market size of 154kV HTS cable[100 million won] = Market share(%) × Line length of 154kV underground cable[c-m] × Cable unit cost[100million won/c-m]------(3)

Market size of 345kV HTS cable[100 million won] = Market share(%) × Line length of 154kV underground cable[c-m] × Cable unit cost[100million won/c-m]------(4)

Table 4 An itemized statement of KEPCO's investment in unit cost in 2000[Unit : (100million won/c-m) x 10^{-5}

Category	Voltage class	
	345kV OF Cable	154kVCV Cable
Material	1,608	631
Labor	196	149
Other	79	59
Total	1,883	839

In Tables 5 and 6, the estimates of underground cable line lengths and the market size of HTS cables in Korea between 2008 and 2020, calculated by Formula(3) and Formula(4) are provided.

Table 5 Estimation of underground cable line length in Korea[Unit : c-km]

Year	154kV line length	345kV line length	Total line length
2008	1,751(452)	126(33)	1,877(485)
2009	1,805(506)	130(37)	1,935(543)
2010	1,860(561)	134(41)	1,994(602)
2011	1,901(602)	137(44)	2,038(646)
2012	1,942(643)	140(47)	2,082(690)
2013	1,985(686)	143(50)	2,128(736)
2014	2,028(729)	146(53)	2,174(782)
2015	2,069(770)	149(56)	2,218(826)
2016	2,114(815)	152(59)	2,266(874)
2017	2,162(863)	156(63)	2,318(926)
2018	2,209(910)	159(66)	2,368(976)
2019	2,257(958)	162(69)	2,419(1,027)
2020	2,307(1,008)	166(73)	2,473(1,081)

Here, the parenthetical number is the length increased from that of 2000.

2.2.3 Evaluation of the economy of HTS cable

As discussed in Section 2.2.1, this study assumed the following to calculate the construction costs of traditional cable and compact HTS cable in the existing ducts when 1GW per line of 154kV compact HTS cable is applied based on the KEPCO's investment in unit cost and to examine their economies.

- ♦ The increased portion of necessary line length by year is based on the length in 2000.
- ♦ The evaluation of the economy is carried out for the years after 2008 when the HTS cable will be applied.
- ♦ As the capacity of superconducting cable is three times the capacity of traditional cable, one-third of the length of traditional cable is applied for the length of super-conduct -ing cable.
- ♦ In the case of 345kV, all transmission lines are installed in the tunnels whereas in the case of 154kV, about 40% are installed in the tunnels and the remaining 60% are installed in the ducts.(as of 2000)
- ♦ Based on the standard tunnel model, six lines are applied for 345kV and eight lines are applied for 154kV.

Table 6 Estimation of market size of HTS cable in Korea [Unit :100 million won]

Year	Market share(%)	154kV market size	345kV market size	Total market size
2008	3.4	129	21	150
2009	6.7	284	47	331
2010	10.0	471	77	548
2011	15.0	758	124	882
2012	21.0	1,133	186	1,319
2013	27.0	1,554	254	1,808
2014	33.0	2,018	329	2,347
2015	40.0	2,584	422	3,006
2016	48.0	3,282	533	3,815
2017	56.0	4,055	664	4,719
2018	63.0	4,810	783	5,593
2019	69.0	5,546	897	6,443
2020	74.0	6,258	1,017	7,275

Based on above assumptions, the economies are compared and examined. Table 7 shows the construction cost comparison between 154kV class HTS cable and XLPE cable including the cable unit construction cost shown in Table 4 and the installation cost of tunnels/ducts. As shown in Table 7, the cable construction cost of compact HTS cable per line km is about twice that of traditional XLPE cable. However, as its rated capacity per line km is about three times higher, its total line construction cost is lower than that of traditional cable. Also, the compact HTS cable can all be installed in the ducts, whereas the traditional XLPE cable is installed in the tunnels or ducts depending on the combination of transmission and distribution lines. Therefore, when this installation cost is included, the total construction cost of HTS cable(ducts) is one fourth less than that of traditional XLPE cable(tunnels). A three-fourth capital cost reduction can be expected.

This paper compared and examined the economies of traditional cable and HTS cable based on KEPCO's investment in unit cost shown in Table 4 and the underground transmission cable installation plan shown in Table 5. For the evaluation of economies, the length of cable line increase estimated based on the data of 2000 and total market size estimated considering market share of HTS cable are shown in Tables 5 and 6, respectively. Method (A) calculates the cost of cable and the cost of tunnels and ducts while taking into account the market share of superconducting cable when cable lines are increased, and it is expressed by Formula(5). Method (B) calculates the cost of traditional cable line increase without taking into account the market share of superconducting cable, and it is expressed by Formula(6).

Table 7 Comparison of construction costs between cables of interest(in case of 1GW)

Item \ Type	HTS cable (for ducts)	CV cable (for ducts)	CV cable (for tunnels)
Rated voltage[kV]	154	154	154
Rated capacity[GVA]	1	0.33	0.33
Number of lines[CCT]	1	3	3
Cable construction cost [100 million won/km•line]	16.8	8.4	8.4
Cable construction cost [100 million won/km]	16.8	25.2	25.2
Installation cost of ducts and tunnels[100 million won/km]	9	9	80
Total construction cost [100 million won/km]	25.8	34.2	105.2

Method (A)

Duct[100million won] = [154kV superconducting cable (100%)[km] + 154kV Traditional cable (60%)[km]] × Duct installation cost[100million won/km]

Tunnel[100million won] = {[154kV Traditional cable (40%)[km]÷8] + [354kVTraditional cable(100%)[km]÷6]} × Tunnel installation cost[100million won/km]---------(5)

Method (B)

Duct[100million won] = 154kV Traditional cable (60%) [km] × Duct installation cost [100million won/km]

Tunnel[100million won] = {[154kV Traditional cable(40%) [km]÷8] + [354kV Traditionalcable(100%)[km]÷6]} × Tunnel installation cost [100million won/km]-------------(6)

In Table 8, the economies of traditional cable and superconducting cable calculated using Formulas(5) and (6) are compared and shown by item such as cable cost, tunnel and duct cost and total construction cost. As seen in the table, Method (A), which takes into account the application of superconducting cable in 2008, costs 16 billion won less than Method (B), for which superconducting cable is not applied., In 2011, the construction cost can be reduced by 99 billion won, and in 2020 about 813 billion won.

Table 8 Comparison of the economies of cables by item

Year	Method	Necessary line length[km]		Economy[Unit : 10 billion won]					
		Super-conductor	Traditional	Cable cost		Duct and tunnel cost		Total construction cost	Construction cost difference (B-A)
				Super-conductor	Traditional	Tunnel	Duct		
2008	A	5.3	469	0.9	42.7	21.7	24.1	89.4	1.6
	B		485		44.1	22.5	24.4	91.0	
2009	A	12.3	506	2.1	46.0	23.4	26.6	98.1	3.9
	B		543		49.4	25.2	27.3	101.9	
2010	A	20.0	542	3.4	49.3	25.1	29.1	106.9	6.1
	B		602		54.8	27.9	30.3	113.0	
2011	A	32.3	549	5.4	50.0	25.4	30.6	111.3	9.9
	B		646		58.8	29.9	32.5	121.2	
2012	A	48.3	545	8.1	49.6	25.3	31.8	114.7	14.8
	B		690		62.8	32.0	34.7	129.5	
2013	A	66.3	537	11.1	48.8	24.8	33.0	117.8	20.3
	B		736		67.0	34.1	37.0	138.1	
2014	A	86.3	523	14.5	47.5	24.2	34.1	120.3	26.4
	B		782		71.1	36.2	39.4	146.7	
2015	A	110.0	496	18.5	45.2	23.0	34.8	121.5	33.5
	B		826		75.1	38.3	41.6	155.0	
2016	A	139.7	455	23.5	41.4	21.1	35.5	121.4	42.5
	B		874		79.5	40.5	44.0	164.0	
2017	A	172.7	408	29.0	37.2	18.9	36.1	121.2	52.6
	B		926		84.3	42.9	46.6	173.8	
2018	A	205.0	361	34.4	32.8	16.7	36.6	120.6	62.6
	B		976		88.8	45.2	49.1	183.1	
2019	A	236.3	318	39.7	28.9	14.7	37.3	120.6	72.1
	B		1,027		93.4	47.5	51.7	192.6	
2020	A	266.7	281	44.8	25.6	13.0	38.1	121.5	813
	B		1,081		98.3	50.1	54.4	202.8	

3. Conclusion

The results and features of this study can be summarized as follows.

(1) This study examined a model system configuration of duct type compact HTS cable to be applied to a large city power transmission system.

(2) This study also examined the standard inner diameter of duct by underground cable type and installation method. Based on the results, the maximum external diameter of cable required for the HTS cable to be accommodated in the existing duct is calculated.

(3) Transmission capacity of HTS cable that can be applied to metropolitan areas in 30 years in consideration of the increase in power demand is studied.

(4) In consideration of the cooling aspect and insulation aspect, the maximum external diameter of HTS cable is calculated by voltage class and the voltage class that can be installed in the existing ducts in Korea is studied.

(5) In consideration of mid-long-term power demand prospect and the market share of HTS cable, the line length of underground cable by voltage class and the market size of HTS cable are estimated.

(6) In consideration of the increase of underground cable line length estimated by voltage class and the market share of HTS cable, the economies of HTS cable and traditional cable are compared by item.

(7) The comparison results were as follows: Method (A), which considers the application of superconducting cable in 2008, costs 16 billion won less than Method (B), for which superconducting cable is not applied., In 2011, the construction cost can be reduced by 99 billion won, and in 2020 about 813 billion won.

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