pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.20, No.4, (2018), pp.60~64 https://doi.org/10.9714/psac.2018.20.4.060

Economic analysis of a 22.9 kV HTS power cable and conventional AC power cable for an offshore wind farm connections

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(Received 30 November 2018; revised or reviewed 23 December 2018; accepted 24 December 2018)

Abstract

As the offshore wind farms increase, interest in the efficient power system configuration of submarine cables is increasing. Currently, transmission system of the offshore wind farm uses almost AC system. High temperature superconducting (HTS) power cable of the high capacity has long been considered as an enabling technology for power transmission. The HTS cable is a feasible way to increase the transmission capacity of electric power and to provide a substantial reduction in transmission losses and a resultant effect of low CO2 emission. The HTS cable reduces its size and laying sectional area in comparison with a conventional XLPE or OF cable. This is an advantage to reduce its construction cost. In this paper, we discuss the economic feasibility of the 22.9 kV HTS power cable and the conventional AC power cables for an offshore wind farm connections. The 22.9 kV HTS power cable cost for the offshore wind farm connections was calculated based on the capital expenditure and operating expense. The economic feasibility of the HTS power cable and the AC power cables were compared for the offshore wind farm connections. In the case of the offshore wind farm with a capacity of 100 MW and a distance of 3 km to the coast, cost of the 22.9 kV HTS power cable for the offshore wind farm connections was higher than 22.9 kV AC power cable and lower than 70 kV AC power transmission cable.

Keywords: AC cable, economic analysis, offshore wind farm, superconducting cable

1. INTRODUCTION

The application of wind energy and especially offshore wind energy is a keystone in the policy of several countries for large-scale use of renewable energy. The realization and the grid connection of offshore wind farms are receiving much attention [1].

As high temperature superconducting (HTS) power cables have some merits over conventional cables, several demonstration projects on the HTS cable system are presently under way around the world [2]. All HTS cables have a much higher power density than copper-based cables at similar voltage levels. Moreover, because they are actively cooled and thermally independent of the surrounding environment, they can fit into much more compact installations than conventional copper cables. In addition, HTS cables exhibit much lower resistive losses than conventional copper or aluminum conductors [3].

We analyzed and compared the economic feasibility of the offshore wind farm using the HTS power cable and the AC power cable. The HTS power cable used the 22.9 kV superconducting cable of LS cable&system. The economics of cable were analyzed by calculating capital expenditure (CAPEX) and operating expense (OPEX). This paper compares three cases: 1) 22.9 kV AC power inter-array and export cables of the offshore wind farm 2) 22.9 kV AC power inter-array cables of the offshore wind farm and 22.9 kV HTS power 22.9 kV AC power inter-array cables of the offshore wind farm and 22.9 kV HTS power export cable of the offshore wind farm to the coast and 3) 22.9 kV AC power inter-array cables of the offshore wind farm and 70 kV AC power export cable of the offshore wind farm to the coast.

For all the case studies, the case 2 is more expensive than the case 1, because of higher HTS power cable cost and cheaper than the case 3. These results can be used to economic analysis of the HTS power cable for the offshore wind farm.

2. CONFIGURATIONS OF THE OFFSHORE WIND FARM

2.1. Cable Model of the Offshore Wind Farm

The offshore wind farm submarine cable can be divided into two types of inter-array cables and export transmission cables as shown in Fig. 1.

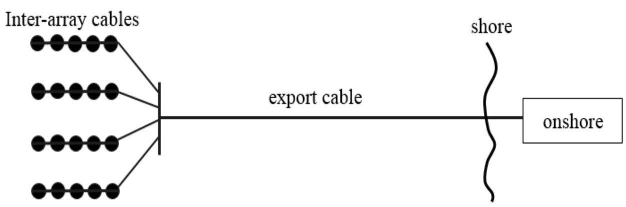

Fig. 1. Configuration of the offshore wind farm.

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The offshore wind farm is connected to 20 wind turbines of 5 MW and the total capacity of the offshore wind farm is 100 MW. The export cable was selected as 3 km. The inter-array cables were fixed with the 22.9 kV AC power cable. Economic analysis was performed with three cases of export cable.

2.2. Three Cases of the Offshore Wind Farm

The export cable of case 1 is the 22.9 kV AC power cable and case 2 is the 22.9 kV HTS power cable and case 3 is the 70 kV AC power cable. Fig. 2-4 show three cases including the HTS power cable.

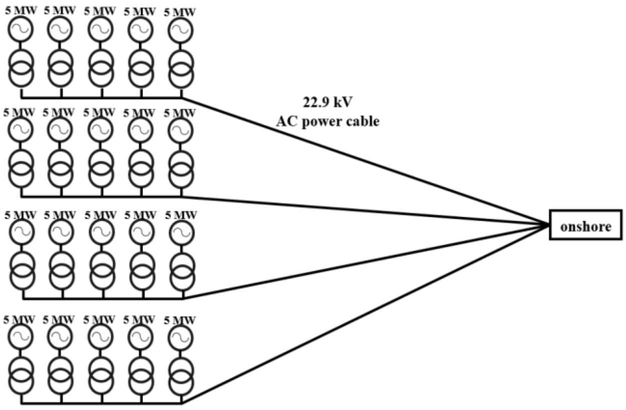

Fig. 2. Case 1 of the offshore wind farm.

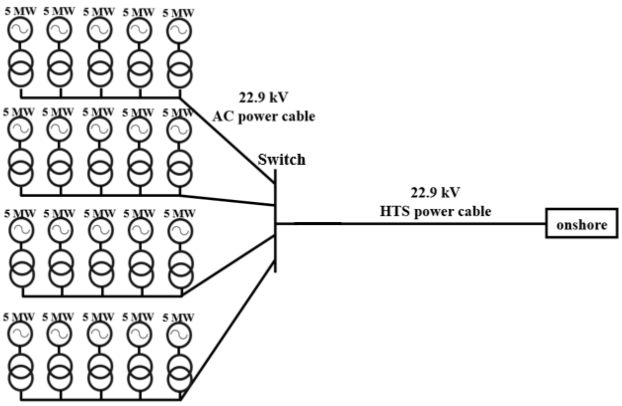

Fig. 3. Case 2 of the offshore wind farm.

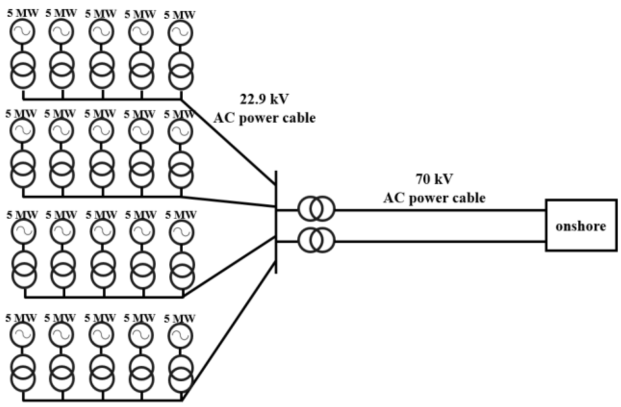

Fig. 4. Case 3 of the offshore wind farm.

3. COST MODELLING OF THE OFFSHORE WIND FARM

3.1. The CAPEX of the Offshore Wind Farm

The CAPEX is the money a company spends to buy, maintain, or improve its fixed assets. The CAPEX of the offshore wind farm covered substation installation cost, cable cost, cable installation cost and reactive compensator cost. The CAPEX of the offshore wind farm using HTS power cable is added cooling system installation cost.

Substation installation cost was calculated as (1) including the offshore wind farm capacity and substation cost.

$$SC = CAP \times C_{station} \tag{1}$$

where
SC : Substation installation cost [KRW]
CAP : The offshore wind farm capacity [MW]
$C_{station}$: Station cost [KRW/MW]

Cable cost and cable installation cost were calculated as (2)-(3) including cable cost and a number of feeders and cable length [4].

$$C_{inst} = C_{cable} \times N_{feeders} \times L_{cable} \tag{2}$$

where
C_{inst} : Total cable installation cost [KRW]
C_{cable} : Cable cost [KRW/km]
$N_{feeders}$: Number of feeders [ea]
L_{cable} : Cable length [km/ea]

$$C_{inst} = \sum_{k=1}^{N_{in}} C_{in} l_{in,k} + N_{ex} C_{ex} l_{ex} \tag{3}$$

where
N_{in} : Number of inter-array cables [ea]
C_{in} : Inter-array cables cost [KRW/km]
$l_{in,k}$: Length of inter-array k feeder cable [km/ea]
N_{ex} : Number of export cables [ea]
C_{ex} : Export cable cost [KRW/km]
l_{ex} : Length of export cable [km]

Reactive compensator is installed to compensate for reactive power caused charging current. In this paper, reactive power is assumed to be reactive power generated from export cable. The leading reactive power amount was calculated as (4) [5].

$$Q_{lead} = \sqrt{3} V_{ex} 2\pi f \frac{V_{ex}}{\sqrt{3}} C_{ex,cap} l_{ex} N_{ex} \times 10^{-6} \tag{4}$$

where
Q_{lead} : The leading reactive power amount generated in the cable [MVar]
f : Grid frequency [Hz]
V_{ex} : Export cable voltage [kV]
$C_{ex,cap}$: Export cable capacitance per unit length [μF/km]

The required reactive power was calculated as (5), a reactor is installed at both ends of the cable, and half of the required reactive power is divided between reactor and STATCOM. The installation cost of the reactive power compensator is calculated as (6) [5].

$$Q_{req} = P_{OWP} \tan\theta \tag{5}$$

$$C_Q = C_{reactor} Q_{lead} + (C_{reactor} + C_{STATCOM}) \frac{Q_{req} N_{ex}}{2} \tag{6}$$

where
Q_{req} : The required reactive power [Mvar]
P_{OWP} : Capacity of the offshore wind farm [MW]
θ : Power factor angle at 0.95 power factor [deg]
C_Q : Total installation cost of reactive power compensator [KRW]
$C_{STATCOM}$: STATCOM installation cost [KRW/MVar]
$C_{reactor}$: Reactor installation cost [KRW/MVar]

The cooling system installation cost was calculated to economic analysis of the HTS power cable for the offshore wind farm (7).

$$Ct_{inst} = (C_{cryo} + C_{inst}) \times N_{cryo} \tag{7}$$

where
Ct_{inst} : The total cooling system installation cost [KRW]
C_{cryo} : The cryocooler cost [KRW/ea]
C_{inst} : Cooling system installation cost [KRW/ea]
N_{cryo} : The number of cryocoolers [ea]

3.2. The OPEX of the offshore Wind Farm

The OPEX is an ongoing cost for running a product, business, or system. The OPEX of the offshore wind farm covered substation loss cost, cable loss cost, operation and maintenance (O&M) cost. The OPEX of the offshore wind farm using HTS power cable is added cooling system loss cost and cooling system O&M cost with excepted cable loss cost.

Substation loss cost was calculated as (8) including active power, loss factor, transmission time and electricity price. The loss factor was selected as 0.8% and transmission time was selected as 6000 hours [6].

$$C_{sub,loss} = P \times lf \times Tt \times C_E \tag{8}$$

where
$C_{sub,loss}$: Substation loss cost [KRW]
P : Active power [MW]
lf : loss factor
Tt : transmission time [hrs]
C_E : Energy generation cost per kWh [KRW/kWh]

Cable loss cost was calculated as (9)-(12) including power loss equation [4].

$$C_{in,loss} = C_E \times 8760 \times 10^{-5} \times \sum_{k=1}^{N_{in}} 3\left(\frac{P_{avg,k}}{\sqrt{3} V_{in} pf}\right)^2 R_{in} l_{in,k} \tag{9}$$

$$C_{ex,loss} = C_E \times 8760 \times 10^{-5} \times 3\left(\frac{P_{AVG} / N_{ex}}{\sqrt{3} V_{ex} pf}\right)^2 R_{ex} l_{ex} N_{ex} \tag{10}$$

$$P_{avg,k} = CF \times P_{Feeder,k} \tag{11}$$

$$P_{AVG} = CF \times P_{OWP} \tag{12}$$

where
$C_{in,loss}$: Inter-array cable annual loss cost [KRW]
$C_{ex,loss}$: Export cable annual loss cost [KRW]
$P_{avg,k}$: Average power of k feeder [MW]
P_{AVG} : Average power of the offshore wind farm [MW]
V_{in} : Voltage level of inter-array cable [kV]
V_{ex} : Voltage level of export cable [kV]
pf : Power factor
R_{in} : Resistance per length of inter-array cable [Ω/km]
R_{ex} : Resistance per length of export cable [Ω/km]
CF : Capacity factor [%]
$P_{Feeder,k}$: Total capacity of k feeder wind turbines [MW]

O&M cost was calculated as (13) including annual fault rate [4].

$$C_{m.t} = C_{repair}\left(\sum_{k=1}^{N_{in}} \lambda_{in} l_{in,k} + \lambda_{ex} l_{ex} N_{ex}\right) \tag{13}$$

where
$C_{m.t}$: O&M cost of the inter-array and export cable cost [KRW]
λ_{in} : Annual fault rate of the inter-array cable [times/year·km]
λ_{ex} : Annual fault rate of the export cable [times/year·km]
C_{repair} : Repair cost of cable at one time [KRW/times]

The cooling system loss cost was defined 20% of the submarine cable loss cost to economic analysis of the HTS power cable for the offshore wind farm.

The O&M cost of the cooling system for the offshore wind farm was calculated as (14).

$$C_{OM,cooling} = 1\% \times C_{inst,cooling} \tag{14}$$

where
$C_{OM,cooling}$: O&M cost of the cooling system [KRW]
$C_{inst,cooling}$: The cooling system installation cost [KRW]

3.3. Parameters of the 22.9 kV HTS Power Cable

The HTS power cable used 22.9 kV LS cable&system data as shown in table I. The capacity of 22.9 kV HTS power cable is 120 MVA. Therefore, a 100MW offshore wind farm can be transmitted with one superconducting cable. 70kV AC cable can transmit with two cables because 70kV AC cable capacity is smaller than 100 MW.

TABLE I
22.9 kV HTS Power Cable of LS Cable & System.

Parameters	Value	Unit
Cable capacity	120	MVA
Short circuit capability	40	kA /0.5s
Cross section of stabilizer	260	mm^2
Cross section of the HTS conductor	34	mm^2
Insulation thickness	4.6	mm
Cross section of the HTS shield	27.7	mm^2
Cable resistance	0.0049	μΩ/km
Cable capacitance	0.26	mF/km

The cable terminations install at both ends of the cable to install the HTS power cable. Superconducting cables can not exceed 1 km in current technology. Therefore, connecting a superconducting cable using a joint box is necessary to create a long transmission line. The HTS power cable installation cost parameters including the cable terminations and the joint boxes are shown in table II.

3.4. Parameters of the AC Power Cable and Offshore Wind Farm

The AC power cable and offshore wind farm parameters are shown in table III-V. Reference of the energy generation unit price is KEPCO industry power cost.

TABLE II
THE HTS POWER CABLE INSTALLATION COST.

Parameters	Value	Unit
HTS power cable price	4,090,000,000	KRW/km
Superconducting wire price	20,000	KRW/m
Required superconducting wires	600,000,000	KRW/km
Number of cables	175	ea
Number of joints	5	ea
Joint box price	200,000,000	KRW
Number of terminals	2	ea
Termination price	550,000,000	KRW
Cost of installation cooling system	2,000,000,000	KRW/ea
Cost of cooling system	3,500,000,000	KRW/ea

TABLE III
22.9 KV AC POWER CABLE COST.

Parameters	Value	Unit
Cable price	54,000,000	KRW/km
Cable installation cost	481,000,000	KRW/km
AC resistance	0.0766	Ω/km
Fault rate	0.0069	times/year·km
Capacitance	0.29	μF/ km

TABLE IV
70 KV AC POWER CABLE COST.

Parameters	Value	Unit
Cable price	631,000,000	KRW/km
Cable installation cost	609,000,000	KRW/km
AC resistance	0.0631	Ω/km
Fault rate	0.00795	times/year·km
Capacitance	0.2	μF/ km
Cable repair cost	7.08	KRW/ times

TABLE V
PARAMETERS OF THE OFFSHORE WIND FARM.

Parameters	Value	Unit
Capacity of the offshore wind farm	100	MW
Capacity of the wind turbine	5	MW
Number of wind turbines	20	ea
Power factor	0.95	
Grid frequency	60	Hz
Capacity factor	30	%
Distance between wind turbines	3.5*rotor diameter (60 m)	km
Minimum distance from wind turbine to substation	0.5	km
STATCOM price	100,000,000	KRW/Mvar
Shunt reactor price	15,000,000	KRW/Mvar
Energy generation unit price	104.43	KRW/kWh

4. RESULTS AND DISCUSSIONS

Total cost of three cases were calculated based on the equations of the CAPEX and the OPEX. The calculation results are shown in table VI-VIII. The case 2 using the 22.9 kV HTS power export cable had the lowest OPEX cost, including loss and maintenance cost. On the other hand, the cable was the most expensive. If the transmission length is long, the economic efficiency of the offshore wind farm using the superconducting cable will decrease due to the price of the superconducting cable as well as the cooling system.

The total cost calculation results are shown in Fig. 5. In the case of the offshore wind farm with a capacity of 100 MW and a distance of 3 km to the coast, case 1 was the most economical of the three cases.

TABLE VI
CALCULATION RESULTS OF THE CASE 1.

Parameters	Value	Unit
Cable price	937,000,000	KRW
Cable installation cost	8,350,000,000	KRW
Reactive compensator price	7,572,000,000	KRW
Cable loss cost	144,000,000	KRW
Capacitance	85,000,000	KRW
Total cost	17,088,000,000	KRW

TABLE VII
CALCULATION RESULTS OF THE CASE 2.

Parameters	Value	Unit
Switch installation cost	30,400,000	KRW
Cable price	12,560,000,000	KRW
Cable installation cost	4,310,000,000	KRW
Reactive compensator price	1,890,000,000	KRW
Cooling system installation cost	5,500,000,000	KRW
Cable loss cost	125,000,000	KRW
O&M cost	96,000,000	KRW
Total cost	24,511,000,000	KRW

TABLE VIII
CALCULATION RESULTS OF THE CASE 3.

Parameters	Value	Unit
Substation installation cost	5,911,000,000	KRW
Cable price	4,075,000,000	KRW
Cable installation cost	6,232,000,000	KRW
Reactive compensator price	3,814,000,000	KRW
Substation loss cost	501,000,000	KRW
Cable loss cost	62,000,000	KRW
Capacitance	60,000,000	KRW
Total cost	20,655,000,000	KRW

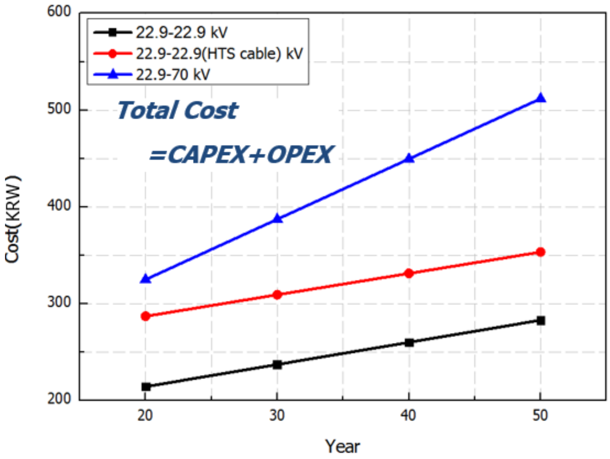

Fig. 5. Calculation results of the three cases.

5. CONCLUSION

This paper analyzed and compared the economic feasibility of the offshore wind farm using the HTS power cable and the conventional AC power cables for the offshore wind farm. Economic analysis of the HTS power cable and the AC power cable were performed by calculating the CAPEX and OPEX. The HTS power cable had lower OPEX cost than the AC power cable. However, The HTS power cable cost is much more expensive than AC power cable cost. The price of superconducting cables and cooling systems will influence the economics of offshore wind farms. These results will be effectively utilized to analyze economic of the HTS power cable for the offshore wind farm.

ACKNOWLEDGMENT

This work was supported by the New & Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20183010025270).

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