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Hou, Peng; Hu, Weihao; Chen, Zhe

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Optimal Selection of AC Cables for Large Scale Offshore Wind Farms

Peng Hou, Weihao Hu, Zhe Chen
Department of Energy Technology
Aalborg University
Pontoppidanstraede 101, Aalborg DK-9220, Denmark
pho@et.aau.dk, whu@iet.aau.dk, zch@iet.aau.dk

***Abstract*—The investment of large scale offshore wind farms is high in which the electrical system has a significant contribution to the total cost. As one of the key components, the cost of the connection cables affects the initial investment a lot. The development of cable manufacturing provides a vast choice space and a great opportunity to optimize the system cost while meets the operational requirements of the offshore wind farms and the connected power systems. In this paper, a new cost model for AC-cable is proposed and the optimal cable selection framework is established using the optimization platform in Matlab. A real offshore wind farm is chosen as the study case to demonstrate the proposed method. Furthermore, the optimization is also applied to an offshore wind farm under development. It can be observed from the results that the proposed optimal cable selection framework is an efficient and systematical way for the optimal selection of cables in large scale offshore wind farms.**

Keywords—cost model; AC-cable; optimal cable selection Matlab; framework

Nomenclature

E_{max}	the maximum electric field intensity that the insulation material can withstand, kV/mm
m	the safe margin, ranged from a factor of 1.2 to 1.6
V_0, I_0	the rated voltage and current, kV and kA respectively
V	the testing voltage at 50Hz, ranged from 2.5 to $3.0V_0$, kV
r_c	the radius of the conductor, mm
R_o	the outer radius of the insulation layer, mm
J_s	the safe current carrying density, A/mm^2
S	the sectional area of cable conductor, mm^2
S_j	the sectional area found in cable list
C_{jacket}	the cost coefficient for cable jacket
C_{filler}	the cost coefficient for cable filler
$C_{insulation}$	the cost coefficient for insulation material
$C_{conductor}$	the cost coefficient for conductor
C_{profit}	profit coefficient
C_{else}	the cost coefficient of employees' salary, rental fee, etc.
C_1, C_2,C_3	the coefficients of Objective Function
x	the section of the cables within the wind farm
V_s, V_r	the voltage at the sending end and receiving end, kV
I_s, I_r	the current at the sending end and receiving end, kA
Z_0, γ	the wave impedance and the propagation constant
ω	the angular frequency
R	the resistance of the cable, Ω/km
L	the cable inductance, mH/km
C	the cable capacitance, μF/km
G	the cable conductance, S/km
l	the length of the cable, km
V_c	the voltage picked up from cable list, kV
P_c	the rated power capacity of selected cable, MW
I_{max}	the maximum current that would go through this cable in full load condition
I_{rated}	the rated current of the cable

I. INTRODUCTION

As one of sustainable resources, wind energy, shows its priorities with many advantages, such as zero-emission, environment friendly and high natural reservation, which make it keep the fastest growing rate comparing with the other renewable resources [1, 2]. The offshore wind farm shows its beneficial on higher wind energy resources' density and stability compared with the on-shore wind farm. However, the total investment on the offshore wind farms is comparatively high. The cost for electrical system has taken a significant proportion in the overall investment. In order to minimize the cost as well as to get a higher power output, some work have been done in [3, 4], which investigate a variety of layouts of large-scale wind parks and the layouts are compared by indices as energy production costs or levelised production costs. However, the transmission cables are selected merely by voltage level without considering the sectional area of each

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cable. Therefore, there is a possibility of over-dimensioned cables.

Power losses within the whole system are another aspect that should be considered in the wind farm design phase. Reference [5] compared the losses between DC wind farms and AC wind farms with different wind turbine cluster topologies. It tried to find the best topology with minimal losses, however, the influence of the cable is not considered in the paper. The selection of optimal voltage level according to total losses within the wind park is specified in [6], which calculates the power losses of cables between wind turbines, however, the line resistance is only calculated by distance without considering the sectional area.

The optimization procedure for offshore wind farm via artificial algorithms has been proposed in [7-9]. The characteristics of wind speed as well as the system reliability are specified whereas the cable cost and the selection criterion are not included. Reference [10] defined a common approximate cost model to calculate the cost of different components such as switchgear, wind turbine, transformer, platform as well as DC and AC cables according to the rated power.

In this paper, a new cost model for AC-cable is proposed and an optimal cable selection framework is established using the optimization platform in Matlab. A real offshore wind farm is chosen as the first study case to demonstrate the proposed method. Then, an offshore wind farm under development is also investigated. The results show that the proposed optimal cable selection framework is an efficient and systematical way for the optimal selection of cables in large scale offshore wind farms.

II. MODEL OPTIMIZATION

The cost model is established based on the characteristics of cable structure, high voltage insulation technology as well as the practical experience of cable price decision. The mathematical models are defined to analyze the influence of both current and voltage ratings on the cable cost. The sequential quadratic programming method (SQP) is used to find the optimal cable selection.

A. Maximum electric field intensity method

The maximum electric field intensity can be found at the interface of the insulation layer and conductor in cable. Therefore the maximum electric field intensity for coaxial cylinder can be written as follow [11]:

$$\frac{E_{max}}{m}=\frac{V}{r_c \ln\frac{R_0}{r_c}} \quad (1)$$

Then, the thickness of the insulation layer can be rewritten as

$$\Delta R=R_o-r_c=r_c(e^{\frac{mV}{E_{max}r_c}}-1) \quad (2)$$

B. Mathmatical Models

In reality, the cable cost can be divided into several parts which can be formulated as:

$$C_{cable}=C_{jacket}+C_{filler}+C_{insulation}$$
$$+C_{conductor}+C_{profit}+C_{else} \quad (3)$$

Where, C_{jacket} and C_{filler} can be regarded as proportional to the distance since the price stays almost the same with different voltage level, while $C_{conductor}$ and $C_{insulation}$ is decided by the voltage level and current respectively. For cables of 66kV and above, a dry-insulation cable is usually conducted, with a lead sheath surrounding the insulation. This part of increased cost is included in C_1 as shown below.

By combining (2) and (3), a new equation is defined as:

$$C_{cable}(x)=[C_1+C_2 r_c(x)^2\left(\frac{mV(x)}{E_{max}r_c(x)}-1\right)+C_3 I_0(x)]l(x) \quad (4)$$

The target of the project is to realize the minimum cost of cable by properly selection of voltage level as well as sectional area. Therefore, the optimization objective function could be defined as

$$\min[\sum_{X=1}^{n} C_{cable}(x)]=\min\{\sum_{x=1}^{n}[C_1+C_2 r_c(x)^2\left(\frac{mV(x)}{E_{max}r_c(x)}-1\right)$$
$$+C_3 I_0(x)]l(x) \quad (5)$$

C. Constraints

In practice, the cable sectional area is selected according to the following rules:

- The current going through the cable cannot be over the maximum current carrying density limitation.

$$S=\frac{I}{J_s} \quad (6)$$

- The voltage drop along the line must be within the limitation.

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix}=\begin{bmatrix} \cosh(\gamma l) & -Z_0\sinh(\gamma l) \\ \frac{1}{Z_0}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix}\begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad (7)$$

The voltage drop along the cable can be calculated according to Line Model which is expressed as above. The theory and the process of formula derivation are detailed in [12]. So the voltage drop can be rewritten as:

$$\Delta V=V_s-V_r=V_s[1-\cosh(\gamma l)]+Z_0 I_s\sinh(\gamma l) \quad (8)$$

Where,

$$Z_0=\sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad (9)$$

$$\gamma=\sqrt{(R+j\omega L)(G+j\omega C)} \tag{10}$$

D. Assumptions

Some necessary assumptions for the optimization problems are:

- The locations of the offshore wind farm as well as each wind turbine are already designed.
- The temperature of the soil and laying way's impacts on cable's properties are neglect, the current carrying density is assumed to be 2A/ mm^2 at all voltage level.
- The lengths of the cables are selected according to the geometrical distance without considering detailed practical situations, such as the barriers, restriction in sea, etc.
- The installation and maintenance costs as well as the costs of the other components such as transformers, circuit breaker, etc. are not taking into account.
- In the study cases, some constants are set up, that is, m is 1.25, V equals to $2V_0$, E_{max} equals to 35kV/mm, G is regarded to zero in this case [13].

E. Optimization method

The target of the project is to find the minimum value of the objective function as expressed in Eq. (5) under the constraints and assumptions. This is a typical optimization problem with constraints.

As one of the popular nonlinear programming methods, sequential quadratic programming method performs well in solving optimization problems under constraints [14]. It gets the optimal solution by generating a series of iterations with Lagrange multipliers. So the constrained optimization problem can be transformed into a sub problem that would be used as the basis of an iterative process [15].

F. Optimal cable selection framework

The procedure of selecting proper cables for one wind farm includes two parts: the voltage level as well as the sectional area. The flowchart of cable selection is shown in Fig.1

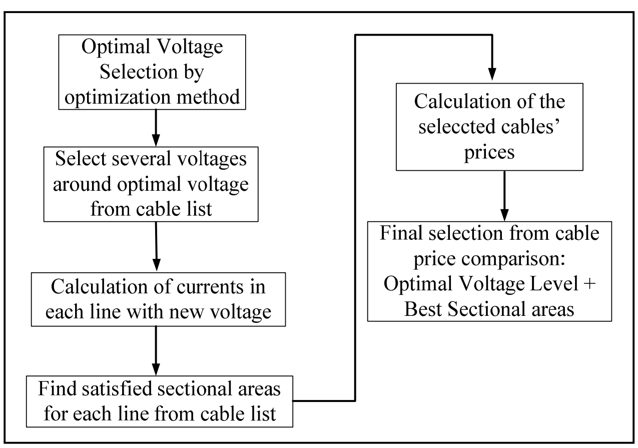

Fig. 1. Optimal cable selection framework

Firstly, the optimal voltages are found by optimization method which is the base for finding the matched cable types in the existing cable list. The optimization method iterates many times in order to find the optimal voltage level for AC-cable in offshore wind farms. Since the voltage level of cable is discrete in reality, the theoretical voltage value is required to be calibrated according to the available types of cables. Based on the obtained optimal voltages, several existing voltages around the optimal point should be studied. The corresponding rated currents, which are the base of finding the corresponding sectional area in cable list, can be calculated for the studied voltage levels. Then the prices of these selected cables may be calculated according to Eq. (4). Eventually, the types of cables which have the minimal cost are selected as the final results by price comparison.

III. Case Study

The cost of cables could be varied a lot since there are plenty of types of cables with different voltage levels and sectional areas of the conductor. So there is a possibility to create an optimal cable selection procedure which can reach the goal of meeting the system requirements as well as minimizing cost.

For a given wind farm, the voltage is inversely proportional to current which means if a higher voltage level is applied, the cost on the insulation materials will be increased while saving the money on conductor. Therefore, there should be a tradeoff somewhere between two parts.

The simulation is implemented on the platform of Matlab software. Two study cases are adopted to verify the feasibility of the proposed method.

A. Case 1: a real wind farm

1) Wind Farm Configuration

A real wind farm is chosen as the first study case. There are 8 wind turbines in each column with interval of 560m. The interval between two columns is 560m as well. For every other column one cable is connected to the transformer station. For the convenience of computation, 5 connection cables are assumed to be with equal length of 2km. The relevant parameters are specified in table I.

TABLE I. Wind Farm I Specification

Name	Information
Wind farm capacity	160MW
Wind Turbine capacity	2MW
Distance from onshore to offshore (average)	21km
Distance from offshore substation to wind farm (average)	2km
Distance between wind turbines	0.56km
Distance between each line	0.56km
Structure	8rows*10columns

According to the wind farm layout in Fig. 2, the wind farm electrical system can be divided into two parts: Collection system (CS) and Transmission system (TS) [16]. It is obviously that there are totally 10 different cables, in other words, 10 different currents within the wind farm.

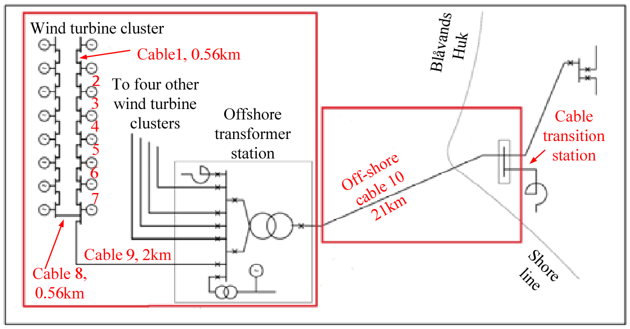

Fig. 2. Wind farm single-line graph (Case 1) [16]

2) *Simulation and results analysis*

The optimal voltages for the wind farm which are found by optimization method are listed in table II. Followed by the results below, three most close voltage levels are selected for each part from the existing cable list for comparisons. All costs are normalized using the base cost which is the cost of a 1000 mm^2 three core XLPE cable with 275kV nominal voltage. This is the three core cable type with highest voltage and current that can be found in the cable list. The related information is specified in [17].

TABLE II. OPTIMAL VOLTAGE WITH CONSTRAINTS

Name	**Optimal results**
Voltage level for CS with constraints	67.72kV
Voltage level for TS with constraints	169.15kV

There are totally 10 different currents within the wind farm. With the selected voltage the most economic sectional area of each current is calculated, then the suitable cables are selected according to the existing types. The results are listed in table III, IV, V and VI. Then S_j is selected from cable list based on I_{max} . The new rated currents, I_{rated}, of selected cables are found in cable list. P is the rated power of the selected cables which can reflect the redudancy of each line. The cost for each cable in the tables below represents for the cost of single cable within the system, in other words, the cost should be mutiplied by its corresponding number of cables if calculating the total costs. The number of Cable1 to Cable7 is 10 while the number of Cable8 and Cable9 is 5 (see fig. 2).

TABLE III. SIMULATION RESULTS FOR CS AT 66KV

Name	**I_{max}/kA**	**S_j/mm^2**	**I_{rated}/kA**	**P_c/MW**	**Cost per km /%**
Cable1	0.0175	95	0.3	34.294	0.110
Cable2	0.0349	95	0.3	34.294	0.110
Cable3	0.0525	95	0.3	34.294	0.110
Cable4	0.0700	95	0.3	34.294	0.110
Cable5	0.0875	95	0.3	34.294	0.110
Cable6	0.1050	95	0.3	34.294	0.110
Cable7	0.1225	95	0.3	34.294	0.110
Cable8	0.1400	95	0.3	34.294	0.110
Cable9	0.2800	95	0.3	34.294	0.110

TABLE IV. SIMULATION RESULTS FOR CS AT 45KV

Name	I_{max}/kA	**S_j**	**I_{rated}/kA**	**P_c/MW**	**Cost per km/%**
Cable1	0.0257	95	0.3	23.382	0.102
Cable2	0.0513	95	0.3	23.382	0.102
Cable3	0.0770	95	0.3	23.382	0.102
Cable4	0.1026	95	0.3	23.382	0.102
Cable5	0.1283	95	0.3	23.382	0.102
Cable6	0.1540	95	0.3	23.382	0.102
Cable7	0.1796	95	0.3	23.382	0.102
Cable8	0.2053	95	0.3	23.382	0.102
Cable9	0.4106	185	0.42	32.735	0.168

TABLE V. SIMULATION RESULTS FOR CS AT 30KV

Name	I_{max}/kA	**S_j**	**I_{rated}/kA**	**P_c/MW**	**Cost per km/%**
Cable1	0.0385	70	0.273	14.185	0.087
Cable2	0.0770	70	0.273	14.185	0.087
Cable3	0.1155	70	0.273	14.185	0.087
Cable4	0.1540	70	0.273	14.185	0.087
Cable5	0.1925	70	0.273	14.185	0.087
Cable6	0.2309	70	0.273	14.185	0.087
Cable7	0.2694	70	0.273	14.185	0.087
Cable8	0.3079	120	0.34	17.666	0.116
Cable9	0.6159	500	0.655	34.034	0.440

The relation of cable cost correspond to the voltage level under the constraints is plotted as blue curve in Figs. 3 and 4 for CS and TS respectively. In Fig. 3, the red triangle represents the minimum cost of CS at 30kV, the blue star is the 45kV case and green triangle is 66kV case. Moreover, the cost of each voltage level is indicated in the bracket with coordinate form.

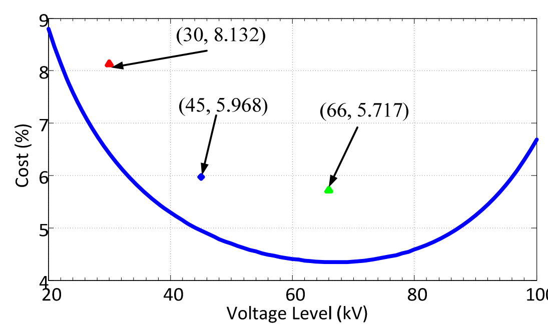

Fig. 3. Cable cost comparisions for CS with constraints (Case 1)

In the same way, the minimum cost of TS at the voltage levels of 110kV, 150kV and 220kV are illustrated with dark triangle, red start and green triangle respectively in Fig. 4.

TABLE VI. SIMULATION RESULTS FOR TS

Name	**V_c**	**I_{max}/kA**	**S_j/mm^2**	**I_{rated}/kA**	**P_c/MW**	**Cost per km/%**
Cable10	110	0.840	300*2	0.53	100.976	0.305*2
Cable10	150	0.616	500	0.655	170.169	0.524
Cable10	220	0.420	500	0.48	249.581	0.612

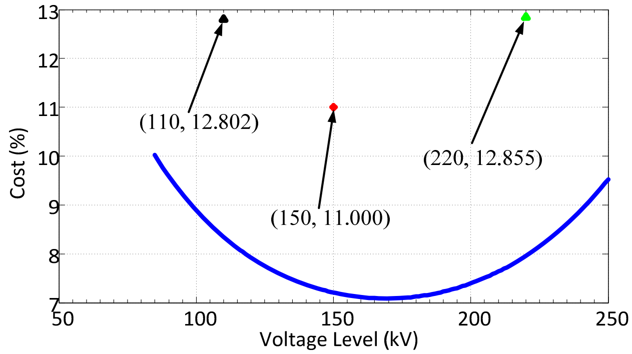

Fig. 4. Cable cost comparisions for TS with constraints (Case 1)

Since the avialable rated current of 110kV cable is 0.825kA which is lower than the highest current that would go through the cable in full load condition, two cables are required if 110kV cable is selected. In conclusion, the best choice for this study case should be 95 mm^2 3-core XLPE cables for collection system operated at 66kV nominal voltage and 500 mm^2 for transmission system operated at 150kV nominal voltage with consideration of constraints. In the real case, the selected cables are 400, 150 or 95mm^2 XLPE-Cu cables, operated at 30kV for the collection system and 630 mm^2 XLPE-Cu cable operated at 150kV for the transmission system [17]. The calculated results for TS coincide with reality while there is still a difference between calculated resutls and reality in CS. The reason is that the difference between 30kV and 90kV is relatively small, as shown in Fig. 3 while the corresponding expenses on substation equipment would make the choice of lower voltage more competitive. Also the estimations on the prices of the corresponding components would introduce uncertainties. Further, many other factors may have to be taken into considerations, such as, reliability and safety, etc.

B. Case 2: a wind farm under development

1) Wind Farm Configuration

The wind farm under development is a new project to be carried out. In our simulation, the total capacity of the wind farm is assumed to be 500MW and the layout is drawn in Fig. 5, the detailed information can be seen in Table VII.

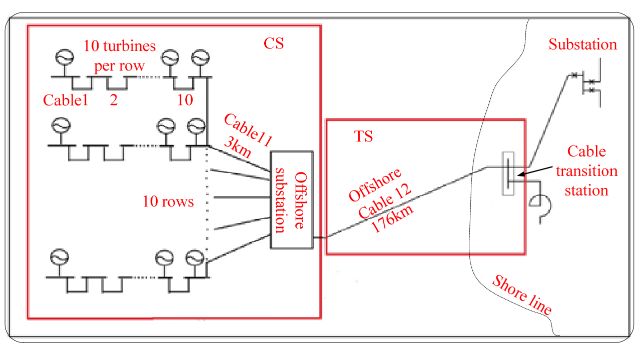

Fig. 5. Cable cost comparisions for CS with constraints (Case 2)

TABLE VII. WIND FARM II SPECIFICATION

Name	Information
Wind farm capacity	500MW
Turbine capacity	5MW
Distance from shore to offshore (average)	176km
Distance from offshore substation to wind farm (average)	3km
Distance between wind turbines	1km
Distance between each line	1km

2) Simulation and results analysis

Since the distance is increasing to 176km in this case, the charging current will be very high. As a consequence, AC cable is not suitable to such situation. In real case, a HVDC system is usually adopted. In this paper, the selection of DC cables is not included. Hence, the optimal cable selection method is only done for CS in Case 2. The simulation is conducted under the full load operation conditions and the wind turbines are controlled under unity power factor control strategy. The optimal voltages found by programs are listed in Table VIII. In this case, several close voltage levels are also selected and according to the optimal cable selection framework, the optimal sectional area for each cable can be found. The results are listed in table IX, X and XI.

TABLE VIII. SIMULATION RESULTS

Name	Optimal results
Voltage level for CS with constraints	96.12kV

TABLE IX. SIMULATION RESULTS FOR CS AT 45KV

Name	I_{max}/kA	S_j/mm^2	I_{rated}/kA	P_c/MW	Cost per km/%
Cable1	0.064	95	0.3	23.382	0.102
Cable2	0.128	95	0.3	23.382	0.102
Cable3	0.192	95	0.3	23.382	0.102
Cable4	0.257	95	0.3	23.382	0.102
Cable5	0.321	120	0.34	26.500	0.120
Cable6	0.385	185	0.42	32.735	0.168
Cable7	0.449	240	0.48	37.411	0.217
Cable8	0.513	300	0.53	41.308	0.344
Cable9	0.577	400	0.59	45.985	0.344
Cable10	0.642	500	0.655	51.051	0.447
Cable11	1.28	500*2	0.655	51.051	0.447*2

TABLE X. SIMULATION RESULTS FOR CS AT 66KV

Name	I_{max}/kA	S_j/mm^2	I_{rated}/kA	P_c/MW	Cost per km/%
Cable1	0.044	95	0.3	34.29	0.110
Cable2	0.088	95	0.3	34.29	0.110
Cable3	0.131	95	0.3	34.29	0.110
Cable4	0.175	95	0.3	34.29	0.110
Cable5	0.219	95	0.3	34.29	0.110
Cable6	0.262	95	0.3	34.29	0.110
Cable7	0.306	120	0.34	38.87	0.129
Cable8	0.350	150	0.375	42.87	0.148
Cable9	0.394	185	0.42	48.01	0.177
Cable10	0.437	240	0.48	54.87	0.226
Cable11	0.875	240*2	0.48	54.87	0.226*2

TABLE XI. SIMULATION RESULTS FOR CS AT 110KV

Name	I_{max}/kA	S_j/mm^2	I_{rated}/kA	P_c/MW	Cost per km/%
Cable1	0.03	185	0.42	80.018	0.203
Cable2	0.05	185	0.42	80.018	0.203
Cable3	0.08	185	0.42	80.018	0.203
Cable4	0.10	185	0.42	80.018	0.203
Cable5	0.13	185	0.42	80.018	0.203
Cable6	0.16	185	0.42	80.018	0.203
Cable7	0.18	185	0.42	80.018	0.203
Cable8	0.21	185	0.42	80.018	0.203
Cable9	0.24	185	0.42	80.018	0.203
Cable10	0.26	185	0.42	80.018	0.203
Cable11	0.52	300	0.53	100.976	0.305

The costs for CS are illustrated in the same way as described above in the first case. The blue dot, green triangle as well as the red dot represents the costs at 45kV, 66kV and 110kV respectively in Fig. 6.

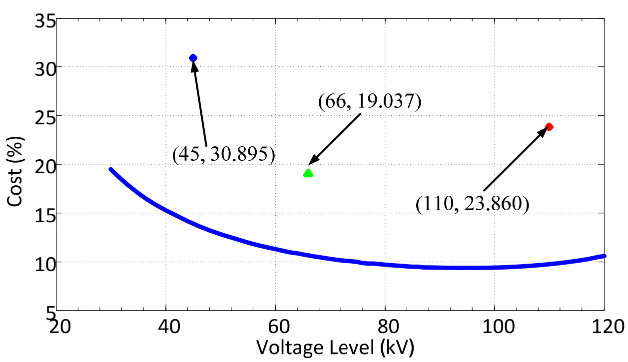

Fig. 6. Cable cost comparisions for CS with constraints (Case 2)

To sum up, the optimal cable selection should be 95, 120, 150, 185 and 240 mm^2 XLPE-Cu cables, operated at 66kV for the collection system according to the simulation results. In reality, more constraints are needed to be added into the optimal cable selection framework so that a comprehensive decision would be made to get a realistic optimal design for an offshore wind farm.

IV. CONCLUSIONS

The electrical system has a significant contribution to the total investment cost of offshore wind farms. In order to minimize the cost while meet the system operational requirement, it is necessary to involve optimization methods into the electrical system design phase. In this paper, a new cable cost model is established. An optimal cable selection framework is proposed to find the optimal voltage level and economic sectional area of cables for collection system and transmission system of an offshore wind farm. The studied cases demonstrate that it is an effective way for optimal cable selection. The proposed method would be applied to various situations by adding different constraints. In the future, more detailed designs related to the wind farm construction and other components will be considered in order to make a comprehensive decision.

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