Global Energy Interconnection
Development and Cooperation Organization

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Volume 3 Number 4 August 2020 (385-397)
DOI: 10.14171/j.2096-5117.gei.2020.04.009
Global Energy Interconnection
Contents lists available at ScienceDirect
https: //www.sciencedirect.com/journal/global-energy-interconnection

Full-length article

Conductor selection and economic analysis of D.R. congo–guinea ±800 kV UHVDC transmission project

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Abstract: Africa is embracing new opportunities featured with industrialization, urbanization and regionalization. Based on co-development of 'Electricity, Mining, Metallurgy, Industry and Trade' and grids interconnection proposed by Global Energy Interconnection Development and Cooperation Organization (GEIDCO), the high-quality hydropower resource of the Congo River can be exploited in large scale under the wide-range interconnected framework of African Energy Interconnection (AEI), forging a new engine for Africa economy. The transmission distance of the Congo River hydropower reaches 6,000 km at its farthest end in North Africa, which brings forth challenges to economics of proposed projects. Under this novel continental energy interconnection scheme in Africa, economics of those projects have not yet been in detail studied. This paper has implemented China's mature engineering experiences and analytical tools of UHVDC project planning into the AEI structure, through exploring the economic behavior of ultra-long distance UHVDC projects in the scope of conductor selection in the Congo River hydropower transmission for the first time, and has provided concerned parties with a technical and analytical results of their economics comparison. This paper has chosen the D.R. Congo - Guinea ±800 kV UHVDC project as a typical example. Its preliminary system planning is introduced and three types of conductor are selected for scheme comparison. Later in this paper, the transmission loss, total investment and equivalent annual cost of the project have been calculated and analyzed. In the final part, sensitivity analysis results of the annual cost to utilization hours, transmission loss, loss tariff and construction cost has been provided.

Keywords: The Congo River Hydropower, Conductor Selection, UHVDC, Economic Analysis, African Energy Interconnection

Received: 26 March 2020/ Accepted: 12 January 2020/ Published: 25 August 2020

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1 Introduction

Since the 21st century, Africa's political situation is generally moving towards stability and African governments have vigorously promoted socio-economic development. The world has witnessed rapid progress of industrialization, urbanization of African countries. The vision of African Union *Agenda* 2063 clearly proposed to develop energy resource in Africa and provide modern, efficient, reliable, affordable, renewable and eco-friendly energy supply for all African families, enterprises, industries and institutions. This goal can be achieved by building regional power pools, national grids and energy projects under African infrastructure development plan. Ensuring energy supply is an essential prerequisite for African sustainable development and clean energy is the foundation to guarantee sustainable energy supply. The construction of a clean energy system centralized with electricity and interconnected power grids can enable long distance and large-scale optimal allocation of clean energy resource, providing an effective and promising solution for future African sustainable power supply. These efforts will inject new dynamism into African economic development and social progress.

In Africa, the theoretical hydro power potential is approximately 4,400 TWh per year, the technical exploitable capacity is estimated to be 340 GW, accounting for 11% of the world total (Hydropower & Dams International Journal, 2016 World Atlas & Industry Guide). At present, the total existing hydropower capacity is approximately 31 GW and another 15 GW is under construction, collectively accounting for less than 15% of the total reserve. Huge potential remains untouched, among which the Congo River has an average annual runoff of approximately 41,000 m^3/s. Its technical exploitable capacity of hydropower is approximately 150 GW. From Kinshasa, located along with the mainstream of the Lower Congo River, to its estuary, the 400 km section of the river has unique geomorphic features of significant falls and the world's second largest flow. The region provides the world's most concentrated hydropower potential and is suitable for large-scale hydropower cascade development. The total installed capacity will reach approximately 105 GW–110 GW if the three-cascade hydropower stations of 'Pioka - Grand Inga - Matadi' are developed coordinately with unified planning.

The Africa continent is endowed with vast clean energy potential. Through intracontinental power interconnection, the cross-time zone, multi-energy complementation of clean energies such as hydro, wind and solar can be achieved, providing sustainable clean electricity supply for the continent. The hydropower resource in the Congo River which takes the full advantage of its unique hydrological feature, is the best available energy source to facilitate co-development of 'Electricity, Mining, Metallurgy, Industry and Trade' and building new engine for economic growth in Africa. Global Energy Interconnection Development and Cooperation Organization (GEIDCO) proposed the general plan of African Energy Interconnection and hydropower delivery in the Congo River as shown in Fig. 1. The plan stands for the purpose of the overall socio-economic and energy development in Africa. It

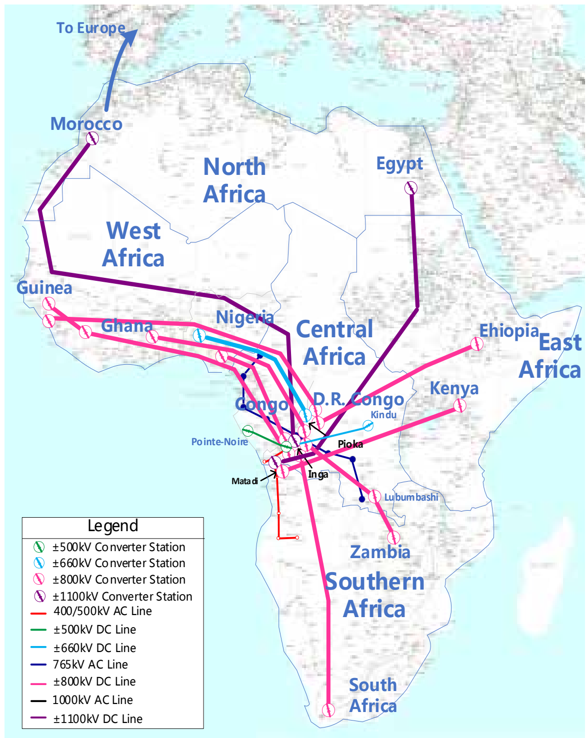

Fig. 1 The overall pattern of the Congo River hydropower transmission

aims to build a strategic energy carrier based on EHV/UHV power transmission channels.

In recent years, China has made enormous efforts in developing UHVAC/DC technologies. In total, 22 UHVAC/DC transmission projects are constructed, including 8 UHV AC and 14 UHVDC projects. Another 9 UHVAC/DC transmission projects are under construction, consisting of 6 UHVAC and 3 UHVDC projects. The total length of ongoing and completed UHV transmission lines reaches 43,000 km. The total transformation (conversion) capacity reaches 430 GVA and cross-regional transmission capacity reaches 140 GW. These practical experiences indicate that the scale effect from UHVDC technologies significantly reduces construction cost and land occupation for long distance and large-scale transmission with favorable economics.

There's tremendous need of cross-regional power delivery for hydropower in the lower Congo River. In the long-term perspective, the proposed transmission capacity will expand to 85 GW with transmission distance from 2,000 km to 4,500 km. Moreover, the distance of 6,000 km to the North Africa at its furthest end is far beyond all existing engineering practice, bringing challenges to the economics of the transmission project. Therefore, this paper has taken an insight of the in-depth study on the economics of large-scale and long distance UHVDC power transmission project for hydropower at the Congo

River. Underlining the principle of sustainable development of Africa and co-development mode of 'electricity, mining, metallurgy, industry and trade', the country of Guinea, which is rich in quality bauxite ores, is taken as a typical example. Therefore, the ±800 kV UHVDC transmission project from D.R. Congo to Guinea has been studied in terms of its selection of conductors and corresponding economics. Later in the article, sensitivity analysis has been conducted for utilization hours, transmission loss tariff and unit line cost.

2 Introduction of the Project System Planning

The Africa Energy Interconnection planning of GEIDCO has preliminarily proposed several UHVDC transmission projects for the down-stream Congo River hydropower. The D.R. Congo – Guinea ±800 kV UHVDC project is the most typical proposal of large-scale and long-distance power supply to support 'Electricity, Mining, Metallurgy, Industry and Trade' policy.

Later contents in this section, boundary conditions of this project including transmission capacity, transmission mode, voltage level and transmission distance are briefly introduced according to [3], among which the choice of transmission distance is further explored in detail.

2.1 Transmission Capacity

Guinea, officially the Republic of Guinea, possesses the world's most bauxite reserve, and significant amount of high-grade iron ore. Its industrial potential of large-scale aluminum and steel smelting is underdeveloped. These reserves are mainly located in regions such as Boke, Boffa and Simandou. In Guinea, the domestic technical exploitable potential of hydropower is about 60 GW with a strong seasonality which is unmatched with the power demand for long-term industrial development. Adopting the co-development mode of 'Electricity, Mining, Metallurgy, Industry and Trade', Guinea will face around 8 to 16 GW of power shortage in the future for mining and metallurgy. This paper preliminarily assumes a local power shortage space of 8 GW from the mining zone in Boke, Guinea.

2.2 Transmission Mode and Voltage Level

The power grids in D.R. Congo of Central Africa and Guinea of West Africa are trans-regional and asynchronous with immense geographic distance. The DC transmission, which has less impact when interconnecting asynchronous grids, flexible dispatching and operation, and larger transmission capacity, is selected. Considering a transmission capacity of 8 GW as assumed above, the voltage level is selected as ±800 kV by principle to equip the ability for long-distance and large-capacity power transmission.

2.3 Transmission Route and Distance

Four transmission routes have been proposed to bypass major lakes, natural reserves, deserts and etc. In Fig. 2, 4 transmission routes have been preliminarily outlined, of which, route 1 and 2 are on land. Route 3 crosses land and shallow water. Route 4 crosses land and deep sea.

Route 1: The route is 4,418 km long, which uses overhead lines and crosses 8 countries, mainly through their central and north regions.

Route 2: The route is 4,535 km long, which uses overhead lines and crosses 8 countries, mainly through their central and south regions.

Route 3: The route is 4,431 km long, which cuts through Atlantic sea along continental shelf. It includes 2,707 km submarine cable and crosses one country (Cote d'Ivoire).

Route 4: The route is 3,898 km long, which passes through deep sea area of the Atlantic. It includes 2,213 km submarine cable and crosses one country (Cote d'Ivoire).

Fig. 2 Proposed transmission routes for D.R. Congo – Guinea transmission project

Route 1 and 2 will avoid crossing the Atlantic Sea, but the length of both routes is over 4,000 km, and more countries (8 countries) are involved. The length of Route 3 is also above 4,000 km, including approximately 2,700 km submarine cable. However, the submarine cable is laid on the continental shelf within shallow sea areas which is more convenient for installation and maintenance comparing to those in the deep sea. Moreover, Route 3 crosses only Cote d'Ivoire. Route 4 is the shortest, it however crosses the Atlantic Sea which is 4,000 to 5,000 m deep.

The sea depth of the Gulf of Guinea is relatively deep and the slope of continental shelf in the North coast is steep. As shown in Fig. 3, only 100 to 150 km offshore, it declines to deep sea area which is 3,000 to 5,000 m deep while in some areas, the altitude falls even faster. The altitude falls to

2,000 m and 3,000 m below at the distance of 40 km and 80 km away from the continental shelf of Ghana respectively. Even the Route 3 has considered the use of the coastal shelf, it still partially crosses deep sea areas with depth of 2,000 to 3,000 m in the northern Gulf of Guinea. Route 4 crosses over a 2,000 km long region which is around 4,000 to 5,100 m deep as shown in Fig. 4.

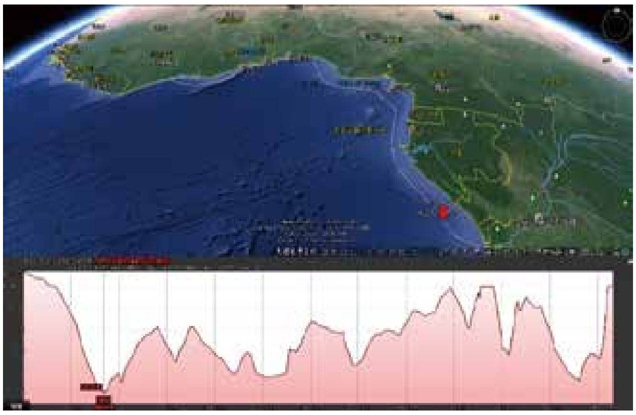

Fig. 3 Illustration of sea depth of Route 3

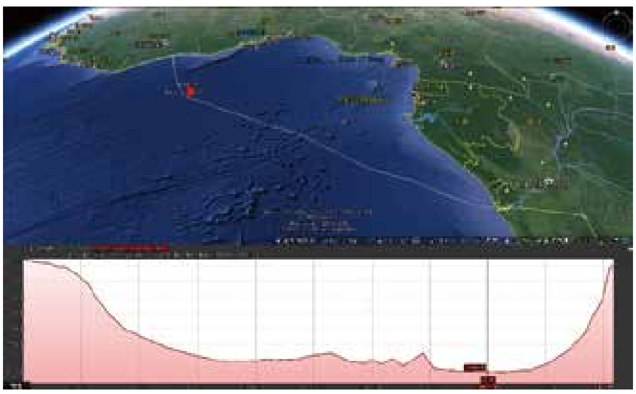

Fig. 4 Illustration of sea depth of Route 4

The technology, manufacturing, installation and maintenance of high voltage, large capacity deep sea power cables are yet immature. There is also no application experience for such cables. Based on the comprehensive needs of technology availability, operation reliability and economics rationality, Route 1 and Route 2 are both feasible. Their transmission length is close which is 4,418 km and 4,535 km respectively. Therefore, this paper has chosen a transmission length level of 4,500 km for analysis.

3 Selection of Conductor

Normally, the increase of transmission capacity and length will scale up the line loss's influence on the project economics. The appropriate selection of conductors with larger cross-sectional area does increase initial investment of the project, whereas it also reduces the line loss which will offset the increased cost in the project's life-circle.

In this section, three types of conductor have been selected, among which the 8×1,000 mm^2, 8×1,250 mm^2 types has already been successfully applied in China's practice while the 8×1,520 mm^2 type is theoretically explored for the ultra-long-distance project. Later in this section, the spacing of sub-conductors, economic current density and overload temperature of the selected conductors have been verified.

3.1 Selection of Conductor Types

Currently, the conductors of constructed ±800 kV UHVDC transmission lines in China are mainly configured as 6-bundled as shown in Table 1. For an equivalent cross section, the 8-bundled configuration has higher conductor ampacity. It also fits for the constrained electromagnetic environment. For better economics, the Shanghaimiao - Shandong ±800 kV UHVDC transmission project, which was completed in December 2017, has adopted 8-bundled 8×JL1/G3A-1250/70 conductors for the first time. This arrangement has balanced its needs of large transmission capacity and requirement to minimize transmission loss to enhance economics.

According to the China's national standard, *Code for designing* ±800 kV *DC overhead transmission line* (GB 50790-2013) and the characteristics of the UHVDC transmission lines, this paper has selected 8×1,000 mm^2, 8×1,250 mm^2 and 8×1,520 mm^2 (not yet applied in practice) conductors to evaluate their economics. These conductors are selected based on the requirements of the above-mentioned system planning, the present inventory in China, and their electrical characteristics, mechanical characteristics and unit cost. The parameters of conductors selected are illustrated in Table 2.

Table 1 Transmission schemes of applied conductors

Project	Conductor Type	Cross-section Area (mm^2)	Transmission Capacity (MW)	Rated Current (kA)	Transmission Distance (km)
Yun Guang Line	6×LGJ-630/45	3,741	5,000	3,125	1,412
Xiang Shang Line	6×ACSR-720/50	4,352	6,400	4,000	1,907

continue

Project	Conductor Type	Cross-section Area (mm^2)	Transmission Capacity (MW)	Rated Current (kA)	Transmission Distance (km)
Jin Su Line	6×JL/G3A-900/40	5,402	7,200	4,500	2,059
Xi Zhe Line	6×JL/G3A-900/40	5,402	8,000	5,000	1,680
Ha Zheng Line	6×JL/G3A-1000/45	6,014	8,000	5,000	2,210
Shanghaimiao to Shandong Line	8×JL1/G3A-1250/70	10,017	10,000	6,250	1,238

Table 2 Selected conductor types and parameters

Conductor Type		JL1/G3A -1000/45	JL1/G3A -1250/70	JL1X/G2A -1520/125
Structure	Aluminum Wire Diameter (mm)	4.21	4.58	5.12
	Wire Number	72	76	74
	Steel Wire Diameter (mm)	2.80	3.57	2.88
	Wire Number	7	7	19
Cross-section Area (mm^2)	Aluminum Stranded Wire	1,002.28	1,252.09	1,523.57
	Steel Core	43.1	70.07	123.77
	Total	1,045.38	1,322.16	1,647.34
Conductor Diameter (mm)		42.10	47.35	48.12
Unit Weight (kg/km)		3,108.8	4,011.1	5,212.1
Rated Tensile Strength (N)		221,140	294,230	394,580
Modulus (N/mm^2)		60,600	62,200	65,100
Linear Expanding Coefficient [/106] (1/ ℃)		21.5	21.1	20.5
DC Resistance at 20 ℃ (Ω/km)		0.0286	0.02291	0.01895

3.2 Spacing of Sub-conductors

In terms of sub-span oscillation effects, it is generally believed that sufficient spacing between sub-conductors can avoid sub-span oscillation. Studies within and outside China show that sub-span oscillations can be avoided if the ratio between the sub-conductor and the diameter of the sub-conductor, i.e., S/d, is greater than 13.80 to 18.0; an S/d smaller than 10 is not recommended; if S/d ranges from 10 to 13.8, spacer dampers must be installed to avoid sub-span oscillation.

From the perspective of electrical characteristics, there is an optimum spacing at which the electric field strength on the conductor surface is minimum and the calculation shows that it is smaller than the minimum spacing required to prevent sub-span oscillation. This means that the spacing required to limit sub-span oscillation serves as a controlling condition.

With the increase in the number of sub-conductors, it is difficult to ensure S/d>13.8–18 for large cross-section conductors of UHV lines. Based on the analysis of the design and operation of lines within and outside China, maintaining the S/d within the range of 10–13.8 can also ensure safe operation. Therefore, the spacing of sub-conductors is determined based on this range. The sub-span oscillation can be controlled by adequately increasing the number of spacer dampers.

On the basis of existing constructed projects and research findings over the world. The bundle spacing for this project is selected as shown in Table 3.

Table 3 Sub-conductors spacing and S/d values (mm)

Sub-conductor Number	Sub-conductor Spacing	Whole Conductor Diameter	Sub-conductor Spacing/Sub-conductor Diameter, S/d
8	500	1,307	10.45-11.07

3.3 Economic Current Density

The maximum transmission capacity in normal DC operation should fit the requirement of economic current density. The standard economic current density in China is demonstrated in Table 4.

Table 4 The standard economic current density in China (A/mm^2)

Conductor Material	Utilization Hours		
	Below 3,000 h	3,000 h-5,000 h	Above 5,000 h
Aluminum	1.65	1.15	0.9
Copper	3.0	2.25	1.75

The subjected project is assumed to be a ±800 kV DC transmission line with transmission capacity of 8 GW and utilization hours of 7,000 hours. All three types of conductors' current density are in the range of 0.41-0.63, lower than 0.9 A/mm^2, which meets the standard requirement. The calculation result is shown in Table 5.

Table 5 Calculation Result of Current Density

Conductor Type (mm^2)	Voltage Level (kV)	Transmission Capacity (MW)	Current (A)	Current Density (A/mm^2)
8×1,000	800	8,000	5,000	0.625
8×1,250	800	8,000	5,000	0.500
8×1,520	800	8,000	5,000	0.411

3.4 Overload Temperature

The choice of conductor should be concerned about the safety for overload operation. According to the Code for designing ±800 kV DC overhead transmission line, system long-term overload capacity is defined as 1.1 times of the rated current. In the circumstance of overloading, the temperature of the conductors should not exceed the permissible temperature rating. The permissible current-carrying capacity (also called ampacity) can be evaluated as the equation below.

$$I = \sqrt{(W_R + W_F - W_S)/R_t^{'}} \quad (1)$$

where, I is the permissible ampacity in A; W_R is the radiation heat loss of per unit length by conductor in W/m; W_F is the convection heat loss of per unit length by conductor in W/m; W_S is the solar heat gain rate per unit length by conductor in W/m; $R_t^{'}$ is the DC resistance at the admissible temperature in Ω/m.

$$W_R = \pi D E_1 S_1 \left[(\theta + \theta_a + 273)^4 - (\theta_a + 273)^4\right] \quad (2)$$

$$W_F = 0.57\pi\lambda_f \theta R_e^{0.485} \quad (3)$$

$$W_S = \alpha_S J_S D \quad (4)$$

where, D is conductor outside diameter (m); E_1 is the emissivity of conductor; S_1 is the Stefan-Boltsmann constant, which is 5.67×10^{-8} (W/m^2); θ is the surface temperature of the conductor in ℃; θ_α is ambient temperature; λ_f is the coefficient of heart transfer from conductor surface to ambient air (W/m/℃); R_e is the Reynolds number, and $R_e = VD/v$; V is the wind velocity that is perpendicular to the conductor; v is kinematic viscosity of air (m^2/s), v = 1.32×10^{-5}+9.6(θ_α+θ/2)×10^{-8}; α_S is the solar radiation absorptivity of the conductor; J_S is the solar intensity on the conductor in W/m^2.

In this project, the rated current for each pole is 5,000 A. Its overload current capacity is 1.1 times of the rated value, which is 5,500 A. The calculation results of maximum ampacity and overload temperature of the selected conductors in the circumstance of 70 ℃ all meet the requirements of the designated transmission capacity. The overload temperature is contained within 70 ℃, as shown in Table 6.

Table 6 The Maximum Permissible Current and Calculated Overload Temperature

Conductor Type (mm^2)	Permissible Ampacity At 70 ℃ (A)	Overload Temperature when Delivering 8 GW (℃)
8×1,000	8,203	60.4
8×1,250	9,405	59.7
8×1,520	10,369	58.4

4 Calculation Formulas for Economic Analysis

The economic behavior of the selected conductors implemented in the D.R. Congo - Guinea ±800 kV UHVDC transmission project will be evaluated according to formulas described in this section. The power loss has included corona loss due to the project's long distance.

4.1 Power Loss Calculation

The power loss of the DC transmission project consists of the converter loss and transmission line loss. Normally, the loss of the converter stations takes about 0.5-1% of the rated power, 0.75% in this paper, which gives totally 1.5% for converter stations at two ends. Transmission loss is mainly caused by resistors and corona effects. The latter is usually insignificantly small and neglected. However, as the length of the project is 4,500 km. The corona loss is linearly increased along the distance, which imposes non-negligible impacts to the economics of the DC transmission through more electrical energy loss.

(1) The line loss, voltage decline and transmission efficiency can be evaluated by the equations below.

$$R = \frac{2}{N} \times r \times L \tag{5}$$

$$W = I^2 \times R \times 10^{-7} \tag{6}$$

$$\Delta V = I \times \frac{R}{2} \tag{7}$$

$$eff = 1 - \frac{W}{P} \tag{8}$$

where, W is power loss of the line in 10 MW, I is the rated power (A); R is the total resistance (Ω); N is the number of conductors in a bundle; r is the resistivity (Ω/km); L is the total conductor length (km); eff is the efficiency of transmission. ΔV is the voltage drop of each pole in kV; P is rated transmission power in 10 MW.

(2) Corona inception field strength

The corona can be observed as a bluish glow around high voltage lines. The corona discharge will occur when the potential gradient of the electrical field around the conductor is high enough to form a conductive region by ionization of air. Tests have proven that the inception field strength is less related to polarity. In general conditions, it is accepted that the corona inception field strength in a DC line is the same to the peak value of the corona inception field strength in an AC line. Thus, its calculation can be transformed into the Peek Equation for DC, as shown below.

$$E_0 = 30m\delta\left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \tag{9}$$

where, m is the conductor surface roughness factor that typical values of m is 0.49 and 0.38 under sunny and rainy conditions; δ is the relative air density; r is the radius of the conductor.

(3) Maximum electrical field strength at the conductor surface

The electrical field strength is determined by the voltage level, line geometric configurations (including the numbers, diameter and spacing of sub-conductors, height and spacing of pole conductors). There exist many methods to evaluate the electrical field strength. This paper has implemented the classic formula applied in the ±800 kV UHVDC Xiang Shang Line and Jin Su Line.

$$G = 1 + \frac{(N-1)r}{R} \Bigg/ Nr\ln\left[\frac{2H}{(NrR^{N-1})^{\frac{1}{N}}\sqrt{1+\left(\frac{2H}{S}\right)^2}}\right] \tag{10}$$

$$g_{max} = GU \tag{11}$$

where N is the number of sub-conductors; S is the spacing of sub-conductors in cm; H is the height of pole conductor in cm; r is the radius of sub-conductors in cm; R is the radius of the circle that contains sub-conductors in cm; g_{max} is the average value of the maximum conductor surface electrical field intensity in kV/cm.

(4) Corona Power loss

The corona power loss is affected by many variable factors, which lacks of consensus in terms of theory or empirical conclusions. There are a number of methods to estimate corona, such as comparison method, semi-empirical formula of USSR, Anneberg formula, Kaptzov concept and revised F.W. Peek's method. The results of them varies extensively. Therefore, in reference to the China's ±800 kV Xiang Shang, Jing Su, Ha Zheng, Ning Shao UHVDC lines, the article is preferred to implement Anneberg formula for bipolar DC line in fair weather.

$$P = \left[2U(K+1)K_C nr \times 2^{0.25(g-g_0)}\right] \times 10^{-3} \tag{12}$$

$$K = \frac{2}{\pi} arctan\left(\frac{2H}{S}\right) \tag{13}$$

where, P is corona loss in kW/km, U is conductor to ground voltage in kV; K_C is conductor surface coefficient which is 0.15 for smooth conductors and 0.35 for defective ones; n is number of sub-conductors; r is the radius of sub-conductors; g is the maximum electric field strength on the conductor surface under operating voltage in kV/cm; g_0 is reference values, which is equal to 22δ (where δ is the relative air density); S is the spacing of poles; H is the altitude of conductor.

4.2 Electricity Loss Calculation

The rate of electricity loss (or line loss rate), which is represented by β_T, is the percentage of electricity loss in comparison to the transmitted electricity within a period T.

$$\beta_T = \frac{\int_{t=1}^{T} I_t^2 \times R \times L \times 2dt}{\int_{t=1}^{T} P_t dt} \times 100\% \tag{14}$$

while in operation, the statistic electricity loss rate can be calculated as following.

$$\beta_T = \frac{\int_{t=1}^{8760} \left(\frac{P_t}{2U_t}\right)^2 \times R \times L \times 2dt}{\int_{t=1}^{8760} P_t dt} \times 100\% \tag{15}$$

Considering equivalent operation mode at rated transmission power, the electricity loss rate calculation becomes the following equation.

$$\beta = \frac{\left(\frac{P_e}{2U_e}\right)^2 \times R \times L \times \tau}{P_e \times T_{max}} \times 100\% \tag{16}$$

According to the above formula, the rate of power loss and electricity loss are both related to maximum load utilization hours and loss hours. The maximum load utilization hours $T_{\max}$ varies by each year. The loss hours τ varies accordingly as formula below.

$$T_{\max}=\frac{\int_{t=1}^{T}P_t dt}{P_e}=\frac{\int_{t=1}^{T}U_e I_t dt}{U_e I_e}=\frac{\int_{t=1}^{T}I_t dt}{I_e} \tag{17}$$

$$\frac{\tau}{T_{\max}}=\frac{\dfrac{\int_{t=1}^{T}I_t^2\times R\times L\times 2dt}{I_e^2\times R\times L\times 2}}{\dfrac{\int_{t=1}^{T}P_t dt}{P_e}}\times 100\%=\frac{\dfrac{\int_{t=1}^{T}I_t^2 dt}{\int_{t=1}^{T}I_t dt}}{I_e}\times 100\% \tag{18}$$

The maximum load utilization hours and loss hours are significantly related to the transmission current. When the operation arrangements are determined, the function of average current in measuring period can be derived. Hence, $T_{\max}$ and τ can be calculated with the formulas above.

This paper adopts an equivalent operation method that function $I_t(t)$ is set as a constant I_c in a certain period of T as shown in Fig. 5.

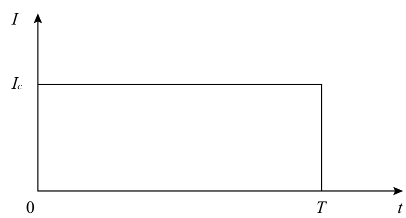

Fig. 5 Illustration of the equivalent operation method when $I_t(t)$ equals a constant I_c

Therefore, $T_{\max}=I_c/I_e\times T$, $\tau=I_c^2/I_e^2\times T$. For ±800 kV UHVDC line with a capacity of 8 GW, the rated current is 5,000 A, the relationship between the maximum load utilization hours and maximum loss hours within the whole year (8,760 hours) is shown in Table 7.

Table 7 Utilization Hours $T_{\max}$ and Loss Hours τ (h)

$T_{\max}$	4,000	4,500	5,000	5,500	6,000	6,500	7,000
τ	1,826	2,312	2,854	3,453	4,110	4,823	5,594
$\tau/T_{\max}$	46%	51%	57%	63%	68%	74%	80%

4.3 Equivalent Annual Cost Calculation

The equivalent annual cost is obtained through converting all costs of a project in to an equivalent annual cost. For comparison, a project design with the lowest equivalent annual cost is considered better. The calculation of equivalent annual cost includes initial investment, annual operation cost and electricity loss cost and the time value of them, as shown below.

$$AC_m=\left\{\sum_{t=1}^{m}I_t(1+r)^{m-t}+\left[\sum_{t=t'}^{m}C_t'(1+r)^{m-t}+\sum_{t=m+1}^{m+n}C_t'\frac{1}{(1+r)^{t-m}}\right]\right\}\times\frac{r(1+r)^n}{(1+r)^n-1} \tag{19}$$

where, AC_m is the annual cost equivalent to the year that the project is completed; m is the construction period; n is the operation period; r is the return on investment or internal rate of return or discount rate; I_t is the annual investment in construction period; C_t' is the annual operation cost; t' is the year when the project is put into operation.

5 Economics of Selected Conductors

5.1 Calculation Boundaries

The system planning of this project has been listed in Table 8. The parameters for equivalent annual cost calculation have been listed in Table 9.

Table 8 Boundary conditions of the project

Transmission Capacity (GW)	Transmission Mode	Voltage Level (kV)	Transmission Distance (km)	Utilization Hours (h)
8	DC	±800	4,500	7,000

Table 9 Main Parameters for Equivalent Annual Cost Evaluation

No.	Items	Unit	Value
1	Operation Time	Years	30
2	Construction Time	Years	2
3	ROI	%	10.00
4	Transmission Loss Tariff	US cents/kWh	10.00
5	Electricity Loss Ratio	%	/
	8×JL1/G3A-1000/45	%	9.47
	8×JL1/G3A-1250/70	%	7.54
	8×JL1X/G2A-1520/125	%	6.31
6	Utilization Hours	Hours	7,000
7	Operation cost/Total Investment	%	2.5

In addition, the transmission loss tariff in project assessment is set as the average feed-in tariff in Guinea which is 10 US cents/kWh.

5.2 Total Investment Estimation

The primary planning reports of Ximeng-Jiangsu, Shanghaimiao-Shandong ±800 kV UHVDC transmission projects are referred to for investment evaluation. Since the 8×1,520 mm^2 conductor has not been applied into practice, the investment of this conductor is therefore estimated according to its influence on tower materials, foundations, earthing, overhead line, fittings and supportive projects due to the increase of the conduction cross sections. The investment of the converter stations refers to the standard of the Haminan-Zhengzhou UHVDC project. The total investment of D.R. Congo-Guinea UHVDC project will be adjusted considering the impacts such as construction period, labor cost outside China.

In this regard, the total project investment applying 8×1,000 mm^2, 8×1,250 mm^2 and 8×1,520 mm^2 conductors are 6.76, 7.03 and 7.68 billion USD.

Table 10 Total Investment Applying Different Conductors

Conductor Type (mm^2)	Unit Line Cost (10,000 USD/km)	Investment Estimation (0.1 Billion USD)		
		Transmission Line	Converter Stations	Total
8×1,000	105.4	47.41	20.14	67.55
8×1,250	111.4	50.15	20.14	70.30
8×1,520	126.0	56.70	20.14	76.84

5.3 Power Loss Evaluation

The subject project applies ±800 kV UHVDC transmission line and 8 GW transmission capacity. Its transmission length is 4,500 km at an altitude of approximately 200 m. The results of power loss calculation for each type of conductor is shown in Table 11. The 8×1,520 mm^2 conductor plan has the minimum power loss which is 9.18%.

Table 11 Calculation Result of Power Loss (10MW)

Conductor Type (mm^2)	Resistance Power Loss	Corona Power Loss	Converter Station Power Loss	Total Power Loss	Power Loss Ratio
8×1,000	90.12	2.68	12.00	104.81	13.10%
8×1,250	71.42	2.35	12.00	85.77	10.72%
8×1,520	59.15	2.32	12.00	73.47	9.18%

5.4 Electricity Loss Evaluation

The utilization hours of the UHVDC project from the Congo River to Guinea are set as 7,000 hours. Under the above-mentioned equivalent operation mode, its equivalent transmission line resistance loss hours are accordingly 5,594 hours. Its corona loss hours are considered at maximum as 8,760 hours. The calculation result shows that the 8×1,520 mm^2 conductor has the minimum electricity loss ratio, which is 7.47%. The electricity loss of each conductor type is as shown in Table 12.

Table 12 Electricity Loss Calculation Result

Conductor Type(mm^2)	Electricity Loss (0.1 TWh)				Loss Rate
	Resistance	Corona	Converter Stations	Total	
8×1,000	50.41	2.35	6.71	59.47	10.62%
8×1,250	39.95	2.06	6.71	48.72	8.70%
8×1,520	33.09	2.03	6.71	41.83	7.47%

5.5 Equivalent Annual Cost Estimation

The results of the equivalent annual costs are demonstrated in Table 13. The 8×1,250 mm^2 conductor provides minimum annual cost by 1.45 billion USD per year.

Table 13 Equivalent Annual Cost Evaluation Applying Different Conductors

Conductor Type (mm^2)	Total Investment (0.1 Billion USD)	Equivalent Annual Cost (0.1 Billion USD/year)	Equivalent Annual Cost per Unit Capacity (0.1 Billion USD/year·kW)
8×1,000	67.55	15.15	189.36
8×1,250	70.30	14.46	180.75
8×1,520	76.84	14.67	183.43

On the basis of the boundary parameters of the equivalent annual cost evaluation, the transmission tariffs applying 8×1,000 mm^2、8×1,250 mm^2 and 8×1,520 mm^2 conductor are 1.6, 1.63 and 1.76 US cents/kWh respectively. Considering the average levelized cost of electricity of hydropower at the Congo River is approximately 3 US cents/kWh, the receiving-end tariff is less than 5 US cents/kWh, which is competitive compared to the average feed-in tariff in Guinea.

Table 14 Transmission Tariff Evaluation

Conductor Type (mm^2)	Utilization Hours (h)	Electricity Loss Ratio	Total Investment (0.1 Billion USD)	Transmission Tariff (US cents/kWh)
8×1,000	7,000	10.62%	67.55	1.60
8×1,250	7,000	8.70%	70.30	1.63
8×1,520	7,000	7.47%	76.84	1.76

6 Sensitivity Analysis

With other boundary conditions unchanged, this paper focuses on the sensitivity analysis of utilization hours, transmission loss tariff and construction cost applying the 8×1,520 mm^2 conductor.

6.1 Utilization Hours

As demonstrated in Table 15, the electricity loss rate of the project presents descending trend with the drop of utilization hours. The 8×1,520 mm^2 conductor scheme has the minimum electricity loss. At 6,000 hours of utilization hours, the electricity loss of 8×1,520 mm^2 and 8×1,520 mm^2 conductor schemes is contained within 8%, which will further fall to 7% and 6% respectively when utilization hours decrease to 5,500 hours.

There exist critical points for the equivalent annual cost of different conductor schemes when the utilization hours vary. The 8×1,520 mm^2 conductor scheme has the minimum annual cost when utilization hours exceed 8,050 hours. The 8×1,250 mm^2 conductor scheme has the minimum annual cost when utilization hours for utilization hours between 4,200 and 8,050 hours. The 8×1,250 mm^2 conductor scheme has the minimum annual cost when the utilization hours are below 4,200.

Table 15 Sensitivity of Electricity Loss to Utilization Hours (hours, 0.1 TWh)

Conductor Type (mm^2)	Utilization Hours	Electricity Loss (0.1 TWh)				Loss Rate
		Resistance	Corona	Converter Stations	Total	
	7,000	50.41	2.35	6.71	59.47	10.62%
8×1,000	6,000	37.04	2.35	4.93	44.32	9.23%
	5,500	31.12	2.35	4.14	37.62	8.55%
	7,000	39.95	2.06	6.71	48.72	8.70%
8×1,250	6,000	29.35	2.06	4.93	36.34	7.57%
	5,500	24.66	2.06	4.14	30.87	7.02%
	7,000	33.09	2.03	6.71	41.83	7.47%
8×1,520	6,000	24.31	2.03	4.93	31.27	6.51%
	5,500	20.43	2.03	4.14	26.60	6.05%

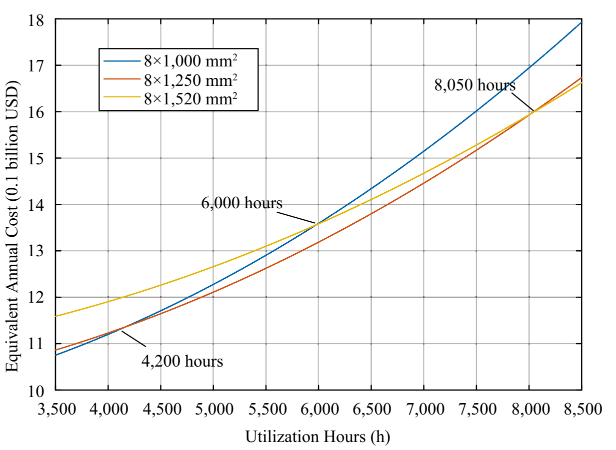

Fig. 6 Sensitivity of Equivalent Annual Cost to Utilization Hours

continue

6.2 Transmission Loss Tariff

The transmission loss cost is directly affected by the transmission loss tariff. The crossing points of annual cost curves appear as the tariff of transmission loss varies. The minimum annual cost can be achieved with 8×1,000 mm^2 conductor scheme when the tariff of transmission loss is less than 3.6 US cents/kWh; with 8×1,250 mm^2 conductor scheme when the tariff is within 3.6 to 13 US cents/kWh; with 8×1,520 mm^2 conductor scheme when the tariff is above 13 US cents/kWh.

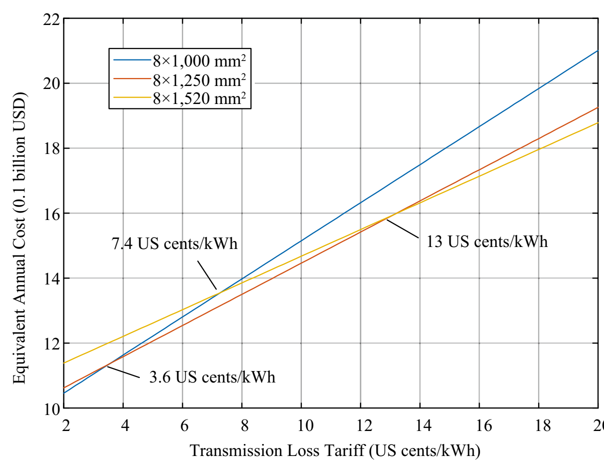

Fig. 7 Sensitivity of Equivalent Annual Cost to Transmission Loss Tariff

6.3 Construction Cost of 8×1,520 mm^2 Conductor

The 8×1,520 mm^2 conductor has not yet been applied in practice. When the unit cost of the transmission line is reduced by over 7.5% of the estimation cost of 1.26 million USD/km (lower than 1.165 million USD/km), the equivalent annual cost of 8×1,520 mm^2 conductor scheme will be less than the 8×1,250 mm^2 conductor scheme.

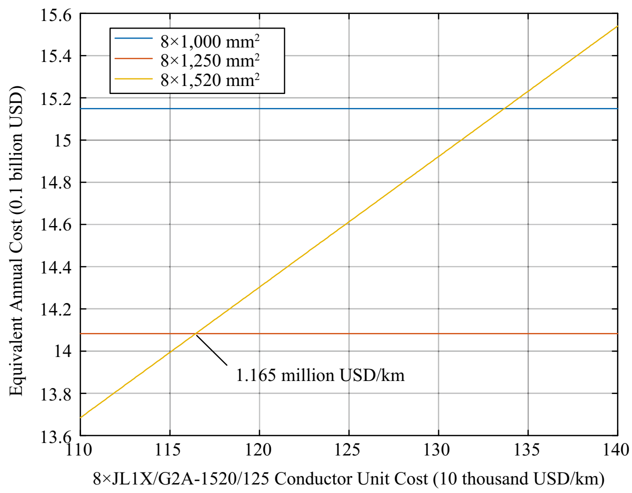

Fig. 8 Sensitivity of Equivalent Annual Cost to Construction Cost of 8×1,520 mm^2 Conductor

7 Conclusion

Africa is embracing new opportunities for sustainable development featuring with industrialization, urbanization and regional integration. By leveraging its abundant mineral and clean renewable energy resource, large scale and quality hydropower development at the Congo River Basin can be accelerated, optimally allocated and efficiently utilized in a wider range in Africa. The process will rely on the co-development mode of 'Electricity, Mining, Metallurgy, Manufacturing and Trade' and power grid interconnection. It will inject strong impetus to industries such as the power sector, mining, metallurgy, manufacturing and international trade, building a new engine for economic development in Africa.

The power transmission distance of hydropower at the Congo River can be as far as 2,000 to 6,000 km. The selection of conductor is crucial for the economics of large capacity and extra-long distance UHVDC transmission. Based on future bauxite mining and metallurgy in Guinea, the D.R Congo-Guinea UHVDC transmission project system planning and the selection of conductors have been proposed. This paper has analyzed the economics and sensitivity of each conductor schemes. The result shows that, a) when the utilization hours are 7,000 hours and the transmission loss tariff is 10 US cents/kWh, the 8×1,250 mm^2 conductor plan has the minimum equivalent annual cost; b) from the perspective of tariff competitivity, the price at the receiving end of the project is no more than 5 US cents/kWh, which is competitive to the average feed-in tariff of 10 US cents/kWh in Guinea; c) regarding the sensitivity of the equivalent annual cost to the of transmission loss tariff and construction cost, the 8×1,520 mm^2 conductor scheme has the minimum equivalent annual cost when transmission loss tariff rises to or above 13 US cents/kWh or the unit construction cost is reduced by over 7.5%.

Most proposed UHVDC projects for the Congo River hydropower have held their utilization hours around 7000 hours due to the unique hydrology of the Congo River Basin [3], which is the foundation of their economic competitivity. This paper's exploration of large-sectional-areas conductors has verified the possible economic feasibility of those ultra-long-distance projects under GEIDCO's African Energy Interconnection scenario. However, the actual trade-off of conductor selection when promoting these projects will require further study on the local economic analysis and other influencing conditions.

Acknowledgements

This work was supported by National Key Reaearch and Development Program of China (2016YFB0900900).

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