Reliability and Economic Comparison of Ultra-long-distance Transmission Mode

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***Abstract*—Combining with the existing transmission technology which is feasible in engineering and theory, four types of ultra-long-distance transmission mode, in terms of UHV AC, UHV DC (±800 kV and ±1 000 kV) and Half-wavelength AC transmission system (HWACT), have been introduced. The reliability and the economy of different modes are compared. Results show that HWACT has obvious advantage in reliability and economy.**

Keywords-* *ultra-long-distance; UHV; reliability; economy

I. INTRODUCTION

The ultra-long-distance transmission mode refers to the transmission mode of transportation distance between 2 000~3 000 km. In recent years, the distance between energy bases and load center increases accordingly. The distance will exceed 2 000 km in the future. The interregional, multinational electricity transmission capacity will reach 373 million kW by 2020[1]. The grid transmission capacity is limited now, which can't afford such massive electricity demand over long distance. Thus developing and researching new ways of transmission is needed to meet the demand of energy development.

The long distance transmission, whether using DC or AC, has been argued for a long time. Combining with the existing transmission technology which is feasible in engineering and theory, UHV, UHVDC and HWACT are suitable for Ultra-long-distance transmission[2-4]. The present research of transmission mode has achieved some results. The [5-8] have calculated the reliability and economic indexes. But it doesn't consider the influence of reactive power compensation equipment during the index calculation of UHV. Meanwhile, the influence of tuning network has not been considered when the electrical distance of HWACT is not enough. The economic index sensitivity of system is also not analyzed. The calculation model is oversimplified.

The paper has analyzed the reliability and economic indexes with the reactive power compensation devices of UHV and the tuning network of HWACT. Finally it obtained reasonable mode of ultra-long-distance transmission power.

II. RELIABILITY CALCULATION

The transmission system is composed of a series of components connected through the series-parallel form, so to get the reliability model of series parallel system based on the relationship of each component can be realized. Calculation of power transmission system using the series-parallel connection model can be performed using the formula of reliability:

The formula for series system forced outage rate and forced outage time are as follows:

$$\lambda_{S-P} = \sum_{i=1}^{n} \lambda_{S_i}^{m_i} \tag{1}$$

$$\gamma_{S-P} = \frac{\sum_{i=1}^{n} \lambda_{S_i}^{m_i} \gamma_{S_i}^{m_i}}{\sum_{i=1}^{n} \lambda_{S_i}^{m_i}} \tag{2}$$

The formula for parallel system forced outage rate and forced outage time are as follows:

$$\lambda_{S_i}^{m_i} \approx \left[\prod_{j=1}^{m_j} \lambda_{ij} \right] \cdot \sum_{j=1}^{m_j} \gamma_{ij} \tag{3}$$

$$\gamma_{S_i}^{m_i} = \frac{\gamma_{S_i}^{m_{i-1}} \cdot \gamma_{m_i}}{\gamma_{S_i}^{m_{i-1}} + \gamma_{m_i}} \tag{4}$$

where λ is forced outage rate of transmission system, the unit is year^{-1}, γ is the system forced interruption duration, the unit is hours per year.

A. UHV System Reliability

UHV is connected with the bus of original 500 kV pivotal substation through 500/1 000 kV step-up transformer and 1 000/500 kV step-down transformer, then the transmission distance reached 2 000 km.

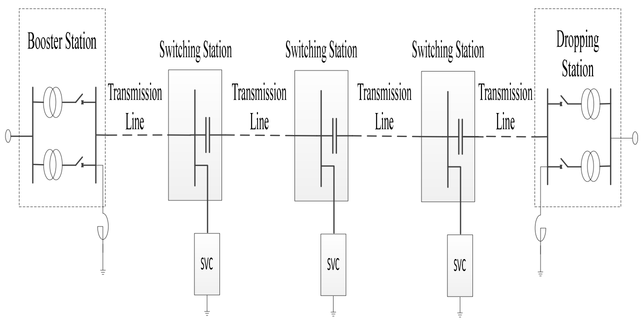


FIGURE I. RELIABILITY CALCULATION MODEL FOR UHV SYSTEM.

The principle and structure of components for UHV and EHV AC power transmission is same, so it can use the existing reliability data of the similar voltage grade[5]. Through calculation, the UHV system's forced outage rate is 1.8051 per year when transmission distance is 2 000 km, meanwhile, forced interruption duration is 1.618 hours per interruption.

B. UHV DC Transmission Reliability

Operation reliability criteria of DC transmission system is calculated according to project.

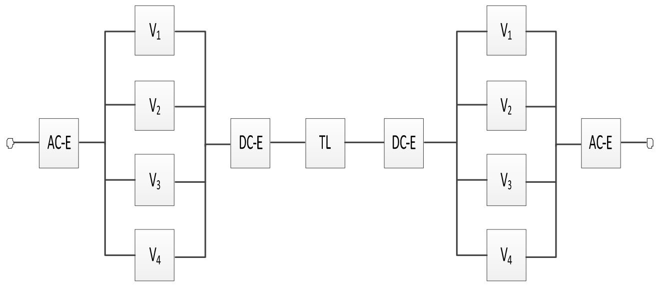


FIGURE II. RELIABILITY CALCULATION MODEL FOR UHV DC SYSTEM.

where AC-E = AC system and auxiliary equipment, including the AC filter or capacitor group and converter transformer; V = converter valve; DC-E = DC primary equipment, including smoothing reactor and DC filter; TL = DC transmission line.

The reliability data of TL in ±800 kV UHV DC use the overhead line reliability data in UHV . And its reliability index can reference from 85% of Brazilian ±600 kV HVDC reliability index.

±800 kV UHV DC system's unipolar forced outage rate is 8.848 year^{-1} and forced interruption duration is 8.937h when transmission distance is 2 000 km.

Reliability model of ±1 000 kV UHV DC is similar with ±800 kV UHV DC. The forced outrage rate of ±1000 kV UHV DC overhead line is 72% of the ±600 kV overhead lines. It can use 85% of reliability index of the ±800 kV system to evaluate other classification index.

±1 000 kV UHV DC system's unipolar forced outage rate is 8.238 year-1 when transmission distance is 3 000 km, and outage time is 7.122h.

C. The Reliability of HWACT System

HWACT is connected with the bus of original 500 kV pivotal substation through step-up transformer and step-down transformer, and the transmission distance reached 3 000 km, there is no switching station in lines.

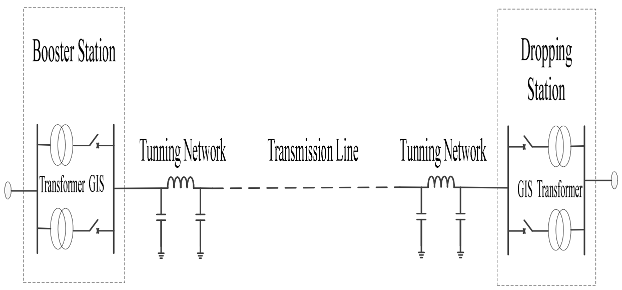
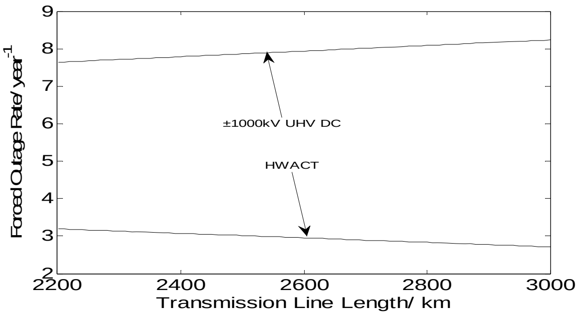


FIGURE III. RELIABILITY CALCULATION MODEL FOR HWACT SYSTEM.

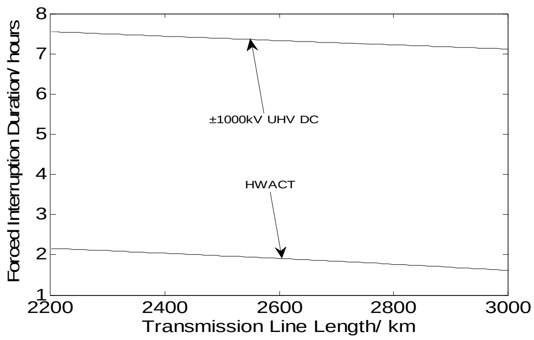
The reliability data of HWACT is same as the UHV. As the components of tuning network is similar to DC equipment (including flat wave reactor and DC filters, etc) of ±1 000 kV UHV DC, so the HWACT can use the reliability parameters of the DC part of ±1 000 kV UHV DC.

The forced outage rate of HWACT is 2.713 year^{-1} and forced interruption duration is 1.614h when transmission distance is 3 000 km.

The ideal distance of HWACT is 3 000 km, if the transmission distance is less than this length, the system need to use manual tuning network to increase electric distance.



(a) The change of the service rate with distance



(b) The change of the stoppage time with distance

FIGURE IV. IMPACT OF TRANSMISSION DISTANCE FOR RELIABILITY.

As Figure 7(a) shows, with the increase of transmission distance, ±1 000 kV UHV DC forced outage rate increased from 7.639 year^{-1} to 8.238 year^{-1}, and HWACT forced outage rate reduced to 2.713 year^{-1} from 3.193 year^{-1}. Forced outage rate of ±1 000 kV UHV DC increased with the increase of transmission distance increases, while that of HWACT system is reducing. As you can see from Figure 7(b), with the increase of transmission distance, ±1 000 kV UHV DC forced interruption duration reduced to 7.122h from 7.553h, meanwhile HWACT system forced interruption duration reduced to 1.614h from 2.160h, so both of them is decreased with the increase of transmission distance.

III. ECONOMIC COMPARISON

Economic comparison of ultra-long-distance transmission mode uses Annual Cost Method. The calculation formula of the Annual Cost Method can be written as follows:

$$N_F = \frac{i(1+i)^n}{(1+i)^n - 1}\{\sum_{t=t_0}^{t=m} Z_t (1+i)^{m-t} + [\sum_{t=t'}^{t=m} U_t (1+i)^{m-t} + \sum_{t=m+1}^{t=m+n} \frac{U_t}{(1+i)^{t-m}}]\} \quad (5)$$

where N_F is the annual cost, i is the investment recovery rate (discount rate), n is engineering economic life, m is the production time of the project, t is the time parameter of the function, t_0 is the start time, t' is the production time of partial project, Z is the amount of investment, U is the operation cost.

The paper supposed that there is adequate power supply in the sending end and enough load in the receiving end of the system. The calculation formula of the cost delivering unit power is

$$F_Y = \frac{N_F}{P} \tag{6}$$

where F_Y is the economic index of power transmission project with the unit RMB /kW·year, W is the project static investment with the unit billion RMB, N_F is the annual cost with the unit is billion RMB and P the transmission power with the unit MW.

The discount rate is 8%, engineering economic life is 30 years, the maintenance costs of the transformer substation, convertor station and line are respectively 2.2% and 1.4% comparing with the total static investment. The power loss is 0.2 RMB /kW·h. The maximum load utilization hours are 4 500 hours and the number of energy consumption is 3500 hours.

A. The Comparison of UHV and ±800 kV UHV DC

The corona loss of UHV is 10 kW/km, active loss is 10% and the line compensation can be considered as the typical parameters. Line active loss of ±800 kV UHV DC is 11.14%, the loss of convertor station at one end of system is 0.7% rated capacity and the same goes for corona loss.

TABLE I COST COMPARISON BETWEEN UHV AND ±800 KV DC TRANSMISSION SYSTEM.

Power Transmission Scheme	***P* / MW**	***W* / Billion RMB**	**N_F / Billion RMB**	**F_Y / (RMB/kW·year)**
UHV AC	5 000	15.806 3	1.644 3	329
±800 kV UHVDC	7 200	21.200 0	2.205 7	306

The conveying unit power comprehensive costs of ±800 kV UHV DC is 6.99% lower than it of UHV. Under the transmission distance of 2 000 km, ±800 kV UHV DC compared with UHV has obvious advantages in economic aspect.

B. The Comparison of HWACT and ±1 000 kV UHV DC System

The active power loss of line in ±1 000 kV UHV DC is 7.05%. The loss at the system end is 0.7%. Line corona loss is 10 kW/km.

HWACT substation uses the hybrid gas insulated switchgear (HGIS). Transmission line adopts double circuit transmission line without switching station. The active and corona loss of line of HWACT are the same as the UHV. Tuning network cost is the same as the equipment cost of DC-E in UHV DC.

TABLE II Cost comparison between ±1 000 kV DC and HWACT transmission system.

Power Transmission Scheme	***P* / MW**	***W* / Billion RMB**	**N_F / Billion RMB**	**F_Y / (RMB/kW·year)**
±1 000 kV UHVDC	9 000	35.500 0	3.651 7	406
HWACT	10 000	30.549 4	3.220 7	322

The conveying unit power comprehensive costs of HWACT is 20.69% lower than it of UHV DC. The HWACT has advantages compared to ±1 000 kV UHV DC in economic consideration When the transmission distance is 3 000 km.

When the transmission line length is shorter than Half-wavelength, appropriate technology should be employed to increase the electrical length up to Half-wavelength.

The economic index is proportional to the transportation distance of HWACT. When HWACT required increasing tuning network to guarantee electric distance, its economy is more obvious.

When the transmission power changed, the economic index of ±1 000 kV UHV DC and HWACT system is also changing.

With the increase of transmission power, the economy of both systems also increases accordingly. The economic index of HWACT is always less than ±1 000 kV UHV DC, so the economy of HWACT is better than the ±1 000 kV UHV DC.

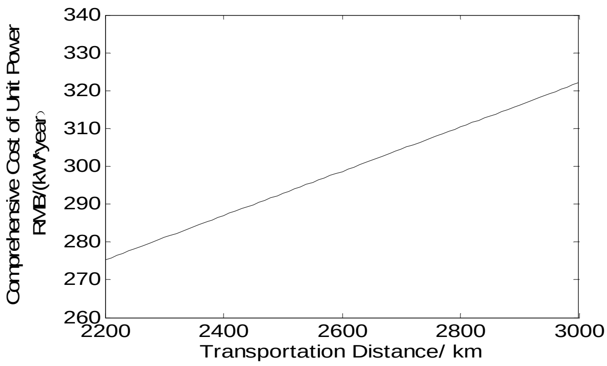


FIGURE V. RELATIONSHIP BETWEEN COST AND DISTANCE FOR HWACT.

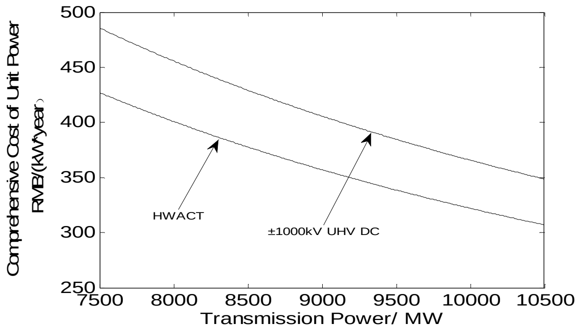


FIGURE VI. RELATIONSHIP BETWEEN COST AND TRANSMISSION POWER FOR HWACT.

IV. CONCLUSION

(1) Although the reliability of UHV is relatively higher when the transmission distance is between 2 000 km and 2 500 km, its limitation should be lower than 2 000 km. The reliability of the HWACT is relatively higher between 2 500 km and 3 000 km.

(2) In the ultra-long-distance transmission, UHV needs a lot of reactive power compensation equipments and thus its economic performance is not good. In UHV DC, the investment of converter station is large and its comprehensive cost of unit power is relatively high. HWACT system needs less equipments and has better economy.

(3) When the transmission distance is 2 000~2 500 km, ±800 kV UHV DC system is better as to the transmission power and the economy index of the system. When the transmission distance is 2 500~3 000 km, HWACT system is better in the aspects of transmission power, reliability and economy.

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