Economic benefit evaluation for renewable energy transmitted by HVDC based on production simulation (PS) and analytic hierarchy process(AHP)

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Abstract. In order to support North and West China's RE (RE) development and enhance accommodation in reasonable high level, HVDC's traditional operation curves need some change to follow the output characteristic of RE, which helps to shrink curtailment electricity and curtailment ratio of RE. In this paper, an economic benefit analysis method based on production simulation (PS) and Analytic hierarchy process (AHP) has been proposed. PS is the basic tool to analyze chosen power system operation situation, and AHP method could give a suitable comparison result among many candidate schemes. Based on four different transmission curve combinations, related economic benefit has been evaluated by PS and AHP. The results and related index have shown the efficiency of suggested method, and finally it has been validated that HVDC operation curve in following RE output mode could have benefit in decreasing RE curtailment level and improving economic operation.

1. Introduction

Owing to the distribution mismatching between RE resources concentrated in North and West regions of China and load centers located in Middle Eastern regions of China, it is necessary to established HVDC for meeting large scale RE electricity transmission requirement. Generally speaking, the conventional daily transmission curves of HVDC will adopt two sections mode, in which high section of curve usually lasts for 14 hours from 8:00 to 21:00, and low one takes the left hours. It is the disadvantage of the mentioned mode for sending region that the transmission line has taken participation in peaking regulation of receiving region, that is to say the sending region needs pay more adjustment ability for the formation of two-section curve. Nowadays, the rapid development of RE in North and West China has been paid more attention for the serve curtailment of wind power and solar power. In order to solve this problem by HVDC, many scholars have done lots of research works, mainly focused on the optimal combination of power sources. The wind power ,solar power and thermal power have been combined as power sources for the HVDC channel, and the transmission curves have set usual one and without strict one, but the latter curve didn't follow the change of RE power output[1]. The optimal model for finding out the wind-thermal power combination have been established for long distance HVDC projects, in which the former one is based on time serious curve of wind power and the latter one takes the duration curve, and the curves of HVDC are represented by the pre-setting utilization hours, which could not be suitable to the RE power output[2, 3]. The largest capacity of singe wind power source for HVDC transmission channel has been figured out, but the high power generation cost will delivered to the receiving region's electricity price, losing the price competency with the local thermal power standard on-grid price [4,5]. It has try to gain the more

efficient curve of HVDC line to enlarge the accommodation scale of renewable indexed by lower curtailment ratio[6,7].

According to trend of RE for large-scale transportation and distribution in China, it has established a HVDC channel model for system simulation analysis firstly in this paper, and has put forward the production simulation analysis model of the interconnection capacity of the RE source. Secondly, a method based AHP has been proposed to evaluate the economic benefit according to different HVDC operation curve schemes. Finally, having taken two typical HVDC projects in Northwest China (signed as HVDC 1 and HVDC 2 respectively) as an testing example, combined with the two types of transmission line curves and based on the production simulation, the comparison and analysis of the scenarios has shown that the HVDC channel has better economic benefits when adopting the operation curves of following the RE output characteristics.

2. Research on HVDC model and basic principle of production simulation(PS) and analytic hierarchy process (AHP)

2.1. HVDC model for power transmission

Considering the operation upper and lower bounds of the HVDC channel, there are two aspects of the output limitation, especially for some HVDC channels which belongs to the regional grid interconnection system. One is the maximum transmission power limit of the contact line such as HVDC, and the other is the maximum exchanging power limit. The constraints for regional power grid interconnection HVDC channel output can be described as:

$$| P_{line} | \leq \min(P_{line.\max} - P_{line.oper}, \Delta P_{ex.\max}) \tag{1}$$

Where, P_{line} represents change amplitude of the HVDC channel power; $P_{line.oper}$, $P_{line.\max}$ respectively on behalf of the HVDC channel's current power level and the maximum power level; $\Delta P_{ex.\max}$ on behalf of the maximum power exchange range between the sending and receiving regions.

2.2. Analysis model of RE based on time series production simulation

Having taken account for the influence of power supply structure, peak-shaving ability, grid constraint, cross-region power exchange and RE output characteristics, combined with the analysis of power grid partitioning, power regulation capacity constraints, adopted optimal RE generation model, the annual electric power generation of RE power could be accurately estimated. In an additional, RE power curtailment ratio assessment of whole year also could be finished under different wind and solar installed capacity, which will be the accepted RE capacity corresponding to current system. In other way, through rational design of the model objective function and constraints, it is possible to evaluate the comprehensive economy of power generation costs, heating costs, transmission costs and pollutant discharge costs.

All the related constraints included in production simulation model could be divided into four types, such as balance of power/heat supply, constraints of various types of generating units, transmission line capacity constraints and curtailment proportion of wind and solar power electricity.

In order to consider the low-carbon and energy-saving benefits of RE sources, objective function are part the optimal overall cost of the system with environmental external costs is optimal, part the lowest total operating cost of thermal power, hydropower and RE power generation, as shown in formula (2),

$$\min F = \sum_{n}^{N} \sum_{t=1}^{T} \sum_{i=1}^{I} ([a_{c,n,i} \cdot P_{c,n,i,t} + (1 - U_{i,t-1})S_i] \cdot U_{i,t} + b_{h,n,i} \cdot P_{h,n,i,t} + c_{w,n,i} \cdot P_{w,n,i,t}) \tag{2}$$

Where, i is the number of units, $i = 1, 2, \cdots\cdots, I$, I is the total number of thermal power units, hydropower stations and RE power plants (wind power plants / photovoltaic power plants); $t = 1, 2, \cdots\cdots, T$, T is the number of simulation time slices; $n = 1, 2, \cdots\cdots, N$, N is the number of power grid regions; F is the operation costs of current power system; $P_{c,n,i,t}$, $a_{c,n,i}$, $P_{h,n,i,t}$, $b_{c,n,i}$, $P_{w,n,i,t}$,

$c_{c,n,i}$ are respectively the thermal power hydropower stations and wind power plants / photovoltaic power generation output and power generation operating costs located in n district; $U_{i,t}$, S_i are respectively for operation status and start costs at n time of thermal power units i; operating cost of wind power plant / PV power unit is set to zero; it had to ensure the priority scheduling of RE power.

2.3. Basic principle of analytic hierarchy process(AHP)

AHP is a popular and widely used method for multi-criteria decision making, which allows qualitative as well as quantitative criteria used in evaluation. It is basically composed of two steps: determine relative weights of decision criteria and determine relative priorities of alternatives. Both qualitative and quantitative information can be compared by using informed judgments to derive weights and priorities.

Firstly, make sure scope of the problem, then put forward specific requirements, understand involved factors and relationship among them, so problem to be solved will be clear based on enough information.

Secondly, foundation of Hierarchy tree. According to nature of the problem and goal to be achieved, it is decomposed into different constituent factors, and then the factors are clustered at different levels according to interrelated influence and affiliation relationship.

Finally a multi-level structural model is established, which includes target layer, criteria layer, and scheme layer. Figure 1 shows the hierarchical relational structure and the dependency of the factors. when analysis level is established two pairs of comparisons can be carried out one by one. Using scoring method to compare their advantages and disadvantages and according to a certain ratio of the scale will determine the quantitative by the expert survey method and in accordance with 1 ~ 9 gradient method the specific criteria, as shown in Table 1 and the formation of comparative judgment matrix.

Table 1. Judgement matrix determines and definition.

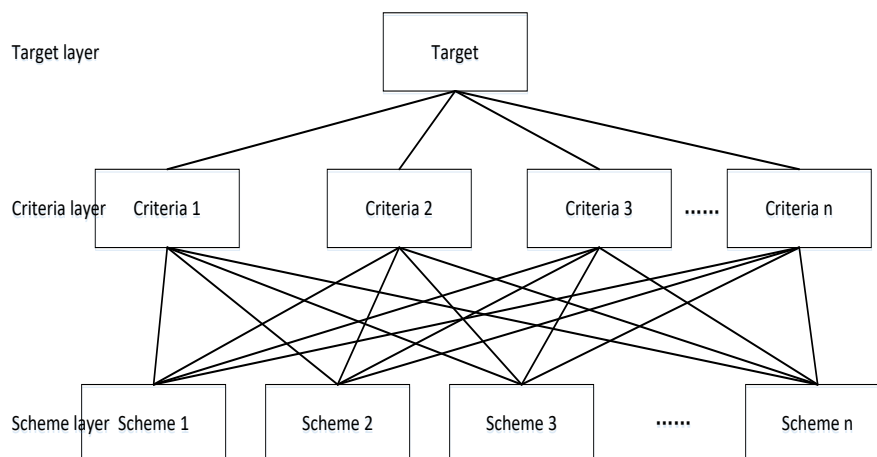| Intensity of importance b_{ij}	definition
1	i and j are equal importance
3	i is somewhat more important than j
5	i is much more important than j
7	i is very much more important than j
9	i is absolutely more important than j
2,4,6,8	Intermediate values
reciprocal	If j is comparted with i，the result is $b_{ji} = 1/b_{ij}$

Figure 1. Basic framework of AHP.

2.4. Single order and consistency test
(1) Level single sort
    Calculate the product of each row element of the judgment matrix M_i

$$M_i = \prod_{j=1}^{n} b_{ij} \quad (\mathrm{i} = 1, 2 \cdots n) \tag{3}$$

Calculate the n th root $\overline{W}_i$ of M_i

$$\overline{W}_i = \sqrt[n]{M_i} \tag{4}$$

Normalize $\overline{W}_i$

$$\overline{W}_i = \frac{\overline{W}_i}{\sum\limits_{j=1}^{n} \overline{W}_j} \tag{5}$$

(2) Consistency test
Calculate largest eigenvalue $\lambda_{\max}$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{b_i}{nW_i} \tag{6}$$

    Where n is the order of the judgment matrix, W_i (i = 1 2 ... n) is vector element in eigenvector of judgment matrix, and b_i (i = 1 2 ... n) determines vector element of the matrix *A* and its characteristic vector *W* calculated as follows,

$$B = A \square W = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix} \tag{7}$$

(3)Calculate judgment matrix consistency *CI*

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

    (4)Calculate judgment matrix consistency ratio *CR* to measure how consistent the judgments have been relative to large samples of purely random judgments. If the CR is greater than 0.1,the judgments are untrustworthy, because they are too close for comfort to randomness and the exercise is valueless or must be repeated.

$$CR = \frac{CI}{RI} \tag{9}$$

    Where *RI* is the mean consistency index which is related to the order matrix n and the RI values for n = 1 2 ... 9 are shown in Table 2. When CR is less than 0.1, matrix consistency is passed otherwise making a judgment again.
    (5) Total sort for all the layers
    Using the single order of calculation results the highest order of the relative order of the highest level. This process is proceeded from top to bottom and then the relative importance of all the factors for the highest target is obtained. The level of the total sort consistency test CR is less than 0.1 the consistency test passed.

$$CR = \frac{\sum\limits_{j=1}^{m} \alpha_j CI_j}{\sum\limits_{j=1}^{m} \alpha_j RI_j} \tag{10}$$

Table 2. *RI* values corresponding to different matrix order n.

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

3. Empirical analysis on the analysis model and comprehensive evaluation method

3.1. Boundary conditions design

Having taken two existing or under construction HVDC projects as example, the capacity of two projects are same as 8000MW. In this paper, the consumption ideas for the cross-region transmitted power could have two choices: one is that the whole 8000MW will be only accommodated in a single province located in receiving region, the other is that all three provinces in this regions will take participation in the consumption as 4000MW, 2000MWand 2000MW. It can be seen that the latter idea will improve the acceptance of related HVDC projects transmission power.

According to the different transportation needs and principles, four operation curves of HVDC transmission line have been proposed including conventional two-stage mode, conventional two-stage mode with low-valence, three-stage mode considering high wind power output at night and multi-stage following RE power output characteristics. The four curve shapes are shown in Figure 2 as follows:
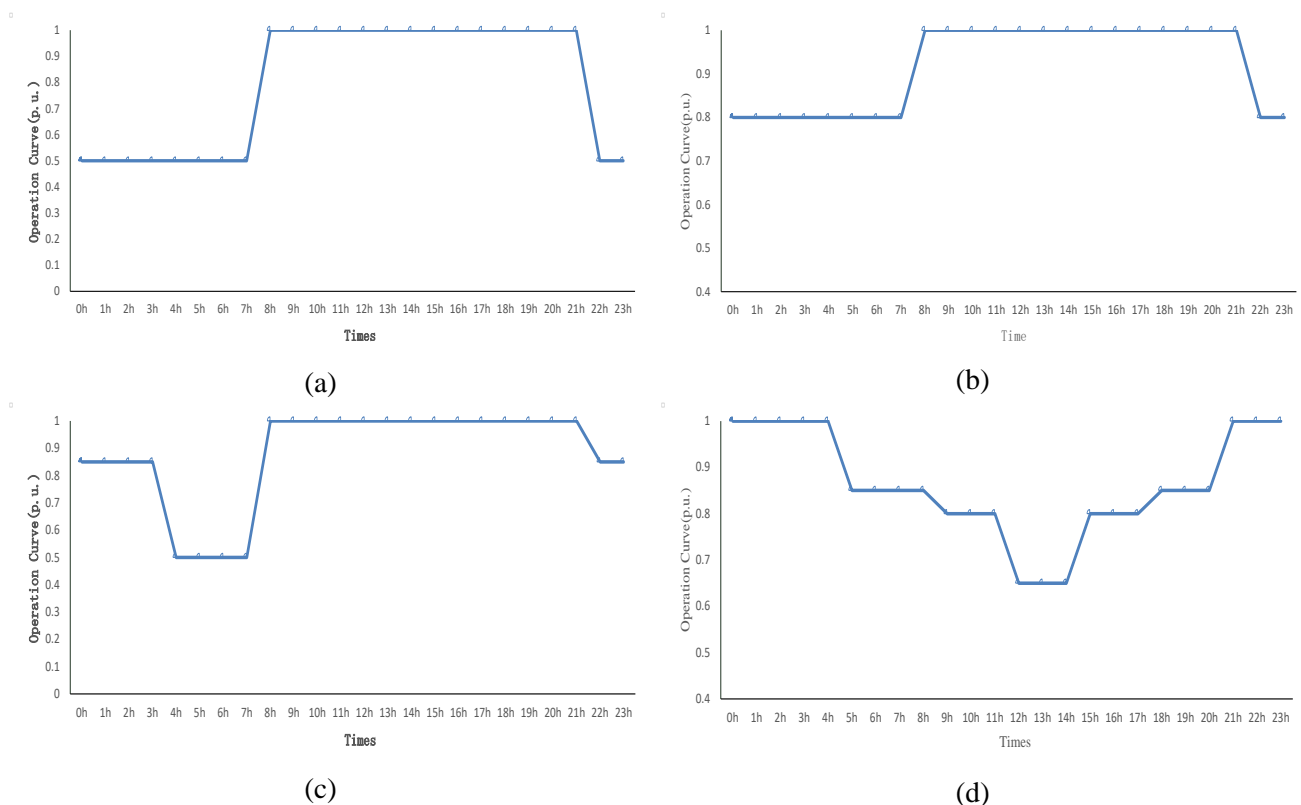

(a)

(b)

(c)

(d)

Figure 2. Four types HVDC operation curves: (a)conventional two-stage mode;(b)conventional two-stage mode with low-valence;(c)three-stage mode considering high power output at night;(d)multi-stage following RE wind power output characteristics.

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3.2. RE curtailment ration of different simulation scenarios

(1) The HVDC transmission curve includes utilization hours, peaking regulation characteristics and other aspects information. In order to promote the delivery of RE electric power, the transmission curve will prefer to higher utilization hours. In sending region, it is equal to increase power market space. In case of utilization hours in same level for two operation curves, the more effective the shape of the power transmission curve equally to participate in the peaking regulation of sending region, in which the pressure will be conducted to receiving regions, the more less RE curtailment ratio is.

(2) The more matching between HVDC power transmission curve and trend of the output characteristics of RE power, the lower curtailment proportion of RE power in sending region is. For example, curve (d) is 196 hours less than curve (b) in utilization hours, but the curtailment ratio for curve (d) is 0.8% lower than curve (b) in sending region, as shown in Table 3.

(3) The more matching between the HVDC power transmission curve and the output characteristics of dominant RE power, the lower curtailment proportion of RE power in sending region is. For example, curve (c) and curve (d) have one common that in daily valley load period the export power scale has been improved, especially curve (d) is 30% higher than curve (c);but during peaking load period, duration time of curve (c) is 6 hours more than curve (d). As a whole, curtailment ratio for curve (d) in sending region is 1.2% less than curve (c). More specifically, the associated RE combination for HVDC transmission channels features that the ratio between wind power and solar power is 7000MW:2800MW, equally to 5:2; in other words, the wind power has taken the dominant place in associated RE power sources combination and also plays main influence on the overall output characteristic.
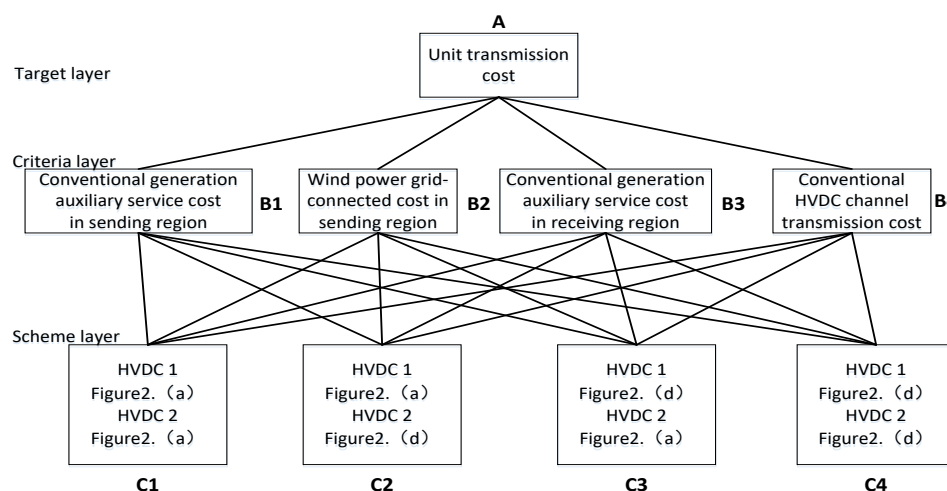
3.3. Analysis of economic evaluation

Figure 3. Economic evaluation based on AHP.

According to transmission curves of existing HVDC channels, based on AHP method, the economic evaluation framework has been proposed as following in Figure 3. Each HVDC transmission channel has two choices for transmission curve shown in Figure 2 (a) and Figure 2 (d), therefore, there will be four schemes evaluated by utilization of the proposed method. Based on target layer elements, judgment matrix of criterion layer index is constructed as shown in Table 4, and judgment matrix is constructed based on criterion layer elements. The judgment matrixes of the index layer are shown in Table 5-8.

Table 3. HVDC utilization hours and corresponding curtaliment ratio (hours,%)

Curve	(a)	(b)	(c)	(d)
Utilization hours	5734	6639	6367	6443
Curtailment ratio	6.9%	5.4%	5.8%	4.6%

Table 4. The judgment matrix (A ~ B) of the criterion layer relative to the target layer.

Curve	B1	B2	B3	B4
B1	1	1/5	1/3	1/7
B2	5	1	4	1/3
B3	3	1/4	1	1/6
B4	7	3	6	1

Table 5. (B1 ~ C) of scheme layer relative to " conventional generation auxiliary service cost in sending region ".

B1	C1	C2	C3	C4
C1	1	2	3	4
C2	1/2	1	4	5
C3	1/3	1/4	1	2
C4	1/4	1/5	1/2	1

Table 6. (B2 ~ C) of scheme layer relative to " wind power grid-connected cost in sending region ".

B2	C1	C2	C3	C4
C1	1	3	3	5
C2	1/3	1	2	3
C3	1/3	1/2	1	3
C4	1/5	1/3	1/3	1

Table 7. (B3 ~ C) of scheme layer relative to "conventional generation auxiliary service cost in receiving region ".

B3	C1	C2	C3	C4
C1	1	1/3	1/3	1/5
C2	3	1	1/2	1/4
C3	3	2	1	1/4
C4	5	4	4	1

Table 8. (B4 ~ C) of the solution layer relative to " conventional HVDC channel transmission cost"

B4	C1	C2	C3	C4
C1	1	5	5	7
C2	1/5	1	1/2	3
C3	1/5	2	1	3
C4	1/7	1/3	1/3	1

Table 9. Determining matrix eigenvector and consistency checking result

JM	EV W	λ_{max}	CI	CR
A~B	(0.053 0.274 0.101 0.571)	4.172	0.058	0.064
B1~C	(0.440 0.354 0.127 0.079)	4.139	0.046	0.052
B2~C	(0.517 0.238 0.168 0.077)	4.104	0.035	0.039
B3~C	(0.073 0.149 0.210 0.568)	4.158	0.053	0.059
B4~C	(0.629 0.128 0.181 0.061)	4.134	0.045	0.050

Table 10. Determining matrix eigenvector and consistency checking result

B	B1	B2	B3	B4	C
C	0.053	0.274	0.101	0.571	TS
C1	0.440	0.517	0.073	0.629	0.532
C2	0.354	0.238	0.145	0.128	0.172
C3	0.127	0.168	0.210	0.181	0.178
C4	0.079	0.077	0.568	0.061	0.118

Then, according to constructed judgment matrix, eigenvectors corresponding to judgment matrixes are calculated, and maximum eigenvalue and coherence index CI are calculated respectively. According to matrix order n (order of two layer judgment matrix in this paper is 4) , corresponding RI value of 0.9 is obtained, and then single order and consistency check are performed. Here, judgment matrix B1 ~ C is used as an example to calculate feature vector, maximum eigenvalue, the consistency index, the consistency coefficient, etc. The other scheme layer for the criterion layer elements, as shown in Table 9.

Finally, combined with the eigenvectors formed by the judgment matrix at each layer, relative weight of the elements corresponding to the criterion layer and relative weights of the elements of the criterion layer and corresponding weights of the target layer elements are formed respectively, and the comprehensive judgment matrix is finally formed. Judgment matrix is shown in Table 10. Consistency check, hierarchical total consistency index, hierarchical total ranking random consistency index, and hierarchical total ranking consistency coefficient. Because CR is less than 0.1, the result of the total ranking is satisfied, the index system is reasonable and the analytic hierarchy process is obvious.

4. Conclusions

In this paper, combined with two HVDC projects including HVDC 1 and HVDC 2, the economic benefit for RE transmitted by HVDC has been implemented based on PS and AHP, with the curves combination for the above projects. The related simulation results have validated the efficiency of proposed method based on PS, and when curves of HVDC follows output characteristic of RE in sending region, the curtailment of RE will correspondingly decreased. According to AHP method, if HVDC operation curve follows change of renewable power output, economic benefit will be maximized among four candidate schemes, and concerned index CR of AHP is also below reasonable upper limits.

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