

An Economic Benefit Evaluation Model and its Application for Optimizing Transmission Capacity of Multinational Interconnections

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Abstract—Multinational power grid interconnections play a critical part in supporting the vision of global energy internet. During the early stages of the Global Energy Internet, the value proposition of multinational interconnections should be carefully investigated in order to stimulate the activities for associated countries in such potential interconnections. This paper proposes a new economic benefit evaluation model which is quantified by using a chronological production cost simulation approach. The economic benefit model comprehensively considered investment costs and the benefits of the decrease of load payments and the increase of net generation revenue due to a transmission project interconnected with different countries. This economic benefit model can assist to quantitatively determine the optimal transmission capacity for multinational interconnections to achieve maximum economic benefits as a whole. In the case study, the economic benefit of an interconnected system of western China and the Gulf States is assessed by using the method proposed in this paper. And the optimal interconnection capacity with maximum benefit is achieved. The case study shows that the proposed method can be used for economic benefit assessment and is of great significance to the multinational and inter-continental transmission interconnections.

Index Terms—Economic benefits, global energy internet, production cost simulation, transmission planning.

I. INTRODUCTION

MULTINATIONAL power grid interconnection has become an objective trend of national power industry development all over the world when faced with uneven distribution of electric demand and energy resources. Global power grid interconnection plays an important role in supporting the vision of global energy internet. In the context of the global energy internet, State Grid Cooperation of China proposes the theoretical concept of a global energy internet and puts forward research on the transmission interconnection

of multinational power grids according to the distribution characteristics of a global large-scale clean energy bases [1], [2]. Multinational interconnections are complex with diverse issues including technical, economic and financial, legal, political, social, and environmental aspects. Besides technical aspects, multinational grid interconnection requires careful and precise evaluation of costs and benefits for a transmission project during the early stages of planning, which is an important part in the global energy internet. It is also critical to note that economic benefits reflects the long-term value of the transmission project for two even more interconnected countries, who need the mutual benefits for resources and electricity. Moreover, investors of such transmission projects need a clear understanding of the revenue return among the whole life cycle of the interconnected project.

The multinational interconnections have been highlighted for rapid development, driven by various factors such as the environment, economy, society and policy [3]. A quantitative analysis of challenges and opportunities of power grid interconnections has been detailed proceeded in [4]. In the multinational interconnection planning, how to choose a transmission interconnection project to obtain the optimal benefit is a key problem to be studied as part of the expansion planning of these large power grids in future years. With the development of the global energy internet, various researches have been conducted on the interconnection projects. In [5], it mainly employed linear programming methods to study the economic and environmental benefits of multilateral power grid interconnections. Moreover, the model minimized the overall system costs of the multilateral power grid interconnection under energy resource and system operational constraints for a single year in Northeast Asia. A model with minimum cost as the objective function was proposed in [6], which can be used to calculate the overall production cost savings and estimate economical electrical energy trading in the interconnected systems. Reference [7] proposed a comprehensive method that minimizes the total costs including various factors such as fuel costs, start-up and shut-down costs, environmental costs and so on to find the optimum operation point in a micro power grid. In these studies, multiple stakeholders may not be taken into consideration, and usually they only aim at minimum cost. In addition, many studies have been performed on investigating the potential of Asia-Europe interconnections [8]–[10]. In [11], it proposed to establish a Northeast Asia Power Grid

Manuscript received January 30, 2016; revised March 29, 2017; accepted July 3, 2017. Date of publication December 30, 2018; date of current version October 10, 2018. This work was supported by the Science and Technology Project of State Grid Cooperation of China (No. 0501000082).

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DOI: 10.17775/CSEEJPES.2017.00200

Interconnected system in an effort to facilitate optimized resource allocation. Generally, in the traditional least cost transmission interconnection planning methods, the optimal transmission interconnected project was chosen on the basis of the minimum cost [12]–[15]. This just provides the economic criterion of the transmission project, and the project still might not be able to provide a satisfactory profit.

However, there is a lack of economic benefits evaluation research considering multiple stakeholders of multi-national interconnections. Without an exactly and reasonable economic benefits evaluation, the interconnected project may likely be faced with a tremendous investment risk. In addition, the assessment of the transmission capacity during the planning stage and forecast of its utilization of long-distance and high-capacity transmission lines are generally lacking.

Therefore, with consideration of the benefits of multiple stakeholders, this paper innovatively presents an economic benefit evaluation model that comprehensively reflects the relationship of costs and benefits. The proposed economic model is used to determine optimal transmission capacity of multinational interconnections. This paper is organized as follows: Section II discusses the proposed method and its application. Section III introduces the background of the study system, and then presents the case results and its relevant analysis. Finally, conclusions are presented in Section IV.

II. ECONOMIC BENEFIT EVALUATION MODEL AND ITS APPLICATION

A. Economic Benefit Evaluation Model for Multinational Interconnections

Economic benefits evaluation is an essential and critical task during the initial planning stage of transnational power grid interconnections [16]. Interconnections allow the usage of the least cost generating resources shared among the interconnected areas and provide an overall cost savings. Alternatively, it allows cheaper energy from a country with surplus supply to be delivered to another country with capacity deficiency or more expensive energy. In general, the economic benefits of the transmission interconnection project for the intention of energy transactions are primarily reflected in two sides. On one hand, these generation companies from the electricity sending countries with abundant and surplus of power generation capacity may obtain much more generation revenue by selling more power; on the other hand, for electricity receiving countries that are generally faced with the challenges of either energy resources shortage or higher electricity prices, power receiving countries may gain much more benefits by purchasing cheaper electricity.

In this paper, an economic benefit model is proposed which contributes to quantitatively evaluating the benefits of multinational interconnections. Based on previous analysis, the economic benefits of interconnected countries include the decrease of load payment and increase of generation revenue. Such benefit for an individual country should be aggregated as a whole for all interconnected countries. When two or more countries are interconnected, the electricity from the lower cost generation units in one country can be sent to another country

with high cost generation units, which results in lowering load payments and providing better generation revenue. Meanwhile, the investment in the transmission line is the cost portion of such interconnections in the cost-benefit analysis. Therefore, net benefit of a transmission project should consider both economic benefits and the costs of investment.

Without a transmission project, total load payment and total net generation revenue in the interconnected system are LP^B and NGR^B , respectively. And with a transmission project, total load payment and total net generation revenue are LP^A and NGR^A respectively; the total cost of the transmission project is set to CT . The benefit calculation is based on the statistics for one year. The total net benefit model is shown as follows:

$$NB_i = (LP^B - LP^A) + (NGR^A - NGR^B) - CT \quad (1)$$

where i denotes different multinational transmission schemes.

1) Load Payment

When the interconnection occurs, it affects power prices on both interconnected sides. Generally, the cost of electricity, namely load payment, is defined as the product of the amount of the load and marginal cost [17], [18].

$$LP = \sum_{t=1}^{8760} \left(\sum_{m=1}^{N_{LD}} (p_{t,m}^{LD} * l_{t,m}^{LD}) \right) \quad (2)$$

where LP (\$) is on behalf of the cost of load in the system. $p_{t,m}^{LD}$ (\$/MWh) denotes the marginal price of the load m . $l_{t,m}^{LD}$ (MWh) denotes the load (MW) amount of the load m at the time t . N_{LD} is the total amount of the loads in the interconnected countries.

2) Net Generation Revenue

$$NGR = \sum_{t=1}^{8760} \sum_{i=1}^{N_G} [g_{i,t} \times p_{i,t} - f_i(g_{i,t})] \quad (3)$$

where N_G is the total number of the generators in the interconnected system. $g_{i,t}$ (MW) is the power of the generator i at the time t . $p_{i,t}$ (\$/MWh) denotes the marginal price of the generator i at the time t .

Generally, the generation cost can be represented as the following equation shown in (4).

$$f_i(g) = a_i(g)^2 + b_i(g) + c_i \quad (4)$$

where a_i , b_i , c_i are the coefficients of the generator unit i .

3) Total Investment Cost of the Interconnected Project

The initial investment costs account for a large part during the transmission interconnected project. It mainly contains the cost of the interconnected lines and substation facilities and so on. The cost calculation equation can be expressed as follows:

$$CT_{total} = (C_T + C_S) \times (1 + overhead)/m \quad (5)$$

In the above calculation, the cost of the interconnected lines and substations are estimation as the following equation respectively.

$$C_T = C_{baseline} \times L \quad (6)$$

$$C_S = C_{basesub} + C_{XFMR} \times Q_{capacity} \quad (7)$$

where C_T denotes the total investment cost of the interconnected lines, and C_S denotes the investment cost of main substations in the project. m is the service life of the interconnected lines. $C_{\text{baseline}}(\$/\text{km})$ is representative of the basic interconnected cost per kilometer, and $L(\text{km})$ is representative of total length of the interconnected lines. $C_{\text{basesub}}(\$/\text{MVA})$ denotes the base costs of the substations in terms of the land costs, construction costs and so on. C_{XFMR} is the investment costs' estimated value of the transformers spreading to each voltage class. $Q_{\text{capacity}}(\text{MV})$ is the generation capacity of these transformers in the project. In addition, *overhead* denotes the indirect costs during the interconnected project. On the basis of the experiences value, it is usually set to 10% [19].

B. The Chronological Production Cost Simulation Model

Based on electricity development objectives and power demand projections of the future multinational interconnected countries, the multinational power grid interconnection system in the future years is established, and then a production cost simulation model considering transmission constraints is constructed.

The production cost simulation model mimics power system operations on the basis of the physical and economic characteristics in the actual power system. And it is diffusely applied to the renewable energy consumption, reliability assessment, and transmission network expansion planning and so on [20]–[22]. The production cost simulation model simulates the operational process of every generation unit on an hourly basis under a predicted time-series load curve, power generation features and fuel costs [23].

The chronological production simulation model can commendably describe the normal and complex activities in the system and then exactly achieve various sorts of physical characteristics and economic performances of the generation system, transmission system and load during the simulation. In the above analysis, generation systems, load, and transmission systems are accurately modeled, as shown in Fig. 1.

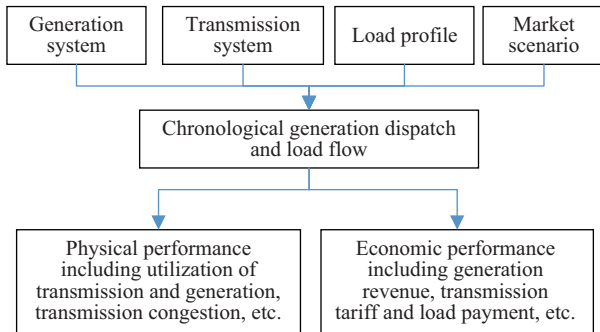


Fig. 1. The framework of the production cost simulation.

This model performs production cost simulation hourly, and its simulation period is generally set to one year. The simulation performs daily generator unit assembly and real-time economic dispatcher ahead in every hour under system security constraints based on power generation, system load, and transmission grid and fuel cost conditions during the whole simulation period. At the end of the simulation, various

relevant statistical performance index can be computed, which can be used to estimate economic benefits of the interconnected project. The basic process of the simulation can be shown in detail in Fig. 2.

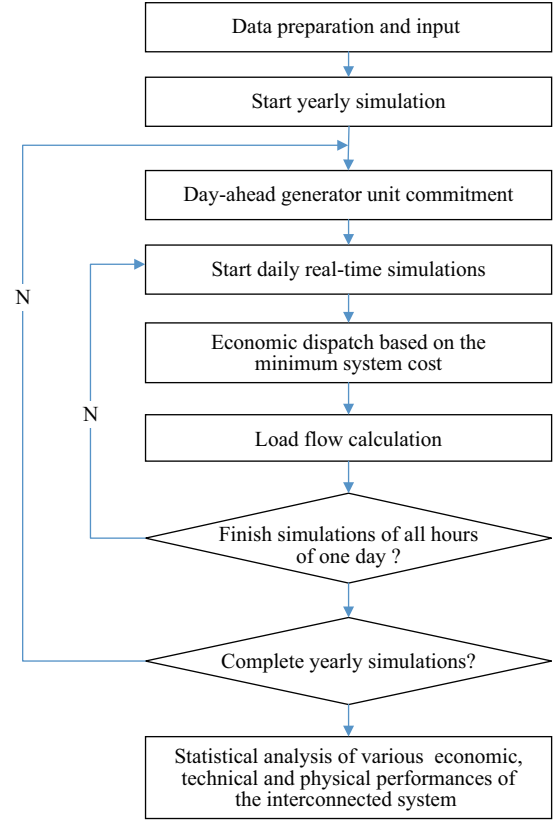


Fig. 2. The process of the production cost simulation.

The key function of the production cost simulation is the generator unit commitment and hourly economic dispatch under various transmission security constraints. The goal is generally set to minimize the production cost in the whole system. The unit commitment model can be found in [24]–[26].

The objective function of the security economic dispatch at the time t can be shown as follows.

$$\min F_t = \sum_{n=1}^{NG} C_n(g_{n,t}) \quad (8)$$

where, NG is the total number of the generator units in the system; $g_{n,t}$ is the active power of the generator unit n at the time t ; $C_n(g_{n,t})$ is the cost function of unit n .

The generation costs of the generator units $C_n[g_n(t)]$ can be generally expressed as a quadratic function as follows:

$$C_n[g_n] = a_n[g_n(t)]^2 + b_n[g_n(t)] + c_n \quad (9)$$

where a_n , b_n , c_n are coefficients of the operation cost of units.

The constraint is shown as follows:

The constraint of power balance in the system is shown as the following equation.

$$\sum_{n=1}^{NG} g_n = \sum_{m=1}^{NL} l_m \quad (10)$$

where NL is the total amount of the loads in the interconnected system; l_m is load amount at the load point m .

The lower and upper limits of the outputs of the generator unit g_n are shown as follows:

$$g_n^{\min} \leq g_n \leq g_n^{\max} \quad (11)$$

where $g_n^{\min}$ and $g_n^{\max}$ are set to express the lower and upper limit of the generator unit n respectively.

The transmission power flow constraints in the interconnected system can be shown as the following formula:

$$|GSF_{ij-k}P_k| \leq f_{ij}^{\max} \quad (12)$$

where GSF_{ij-k} is the generation shift factor of line $i-j$ to the injection of bus k and $f_{ij}^{\max}$ is the transmission flow and thermal limits of the interconnected line $i-j$.

The proposed economic benefits model for multinational interconnections is used not only for two interconnected countries, but also for multiple interconnected countries. And the transmission projects can be one transmission link between two countries or multiple transmission links among multiple countries. Therefore, when performing the statistics of load payment and net generation revenue, all loads and generators in the interconnected countries should be considered.

C. Optimization Analysis of the Transmission Alternative of Multinational Interconnection

According to the proposed economic benefit assessment model, the cost-benefit analysis of the transmission alternatives of multinational interconnections can be carried out to determine the optimal interconnection capacity with the maximum net benefit. According to the previous analysis, there are better chances for sharing cheaper resources among interconnected countries with more interconnection capacity, and the value of the benefits of lower load payment and greater generation tend to be significant. Meanwhile, with the increase of new transmission capacity, the investment cost increases. Therefore, under a certain transmission capacity, the interconnection benefit could be rapidly increasing; with transmission capacity gradually increasing, the rate of the increasing benefit may be slowing down. In this process there is a point of maximum benefit where the transmission capacity is optimal. The overall calculation process of finding optimal transmission capacity is shown in Fig. 3.

The base case of the multinational power grid interconnection system is set to B. New transmission alternatives are set to c_x ; and $c_1, c_2 \dots c_N$ represents interconnection lines with different capacities in an ascending order. $CT_{c1}, CT_{c2} \dots CT_{cN}$ represent the investment cost of $c_1, c_2 \dots c_N$ respectively. The benefit is $NB_{c_x}(x = 1, 2 \dots N)$ as shown in Table I.

Therefore, the relationship between the capacity of the new transmission lines and the interconnection benefits roughly meets the trend shown in Fig. 4. The x axis represents the total capacity of the individual transmission alternatives, and the y axis represents the net economic benefits.

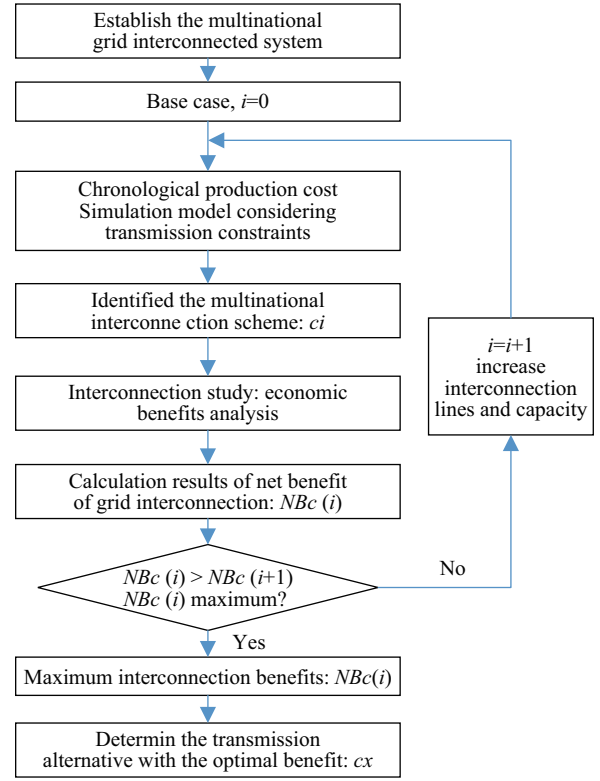


Fig. 3. The flow chart of the proposed method.

TABLE I
COST-BENEFIT ANALYSIS OF DIFFERENT TRANSMISSION ALTERNATIVES

Case	Investment cost	Load payment	Net generation revenue	Net benefit
B	NA	LP_B	NGR_B	/
C_1	CT_{c1}	LP_{c1}	NGR_{c1}	$NB_{c1} = (LP_B - LP_{c1}) + (G_{c1} - G_B) - CT_{c1}$
...	...	...	...	...
C_N	CT_{cN}	LP_{cN}	NGR_{cN}	$NB_{cN} = (LP_B - LP_{cN}) + (G_{cN} - G_B) - CT_{cN}$

III. CASE STUDIES

A. Background of Power Systems of China and the Gulf States

There are abundant coal and clean resources in the western China, whose generation resources are extremely adequate, especially in Sinkiang. In recent years, the installed capacity of renewable resources including the wind power and PV has increased rapidly in Sinkiang. By the end of 2015, the total installed capacity of renewable generation in Sinkiang reached 22,192 MW. In order to promote the usage of clean and renewable resources, Sinkiang has a plan to increase the delivery of clean energy to outside areas. Meanwhile, the Gulf States are facing the challenges of fossil energy shortages with their economy fast growing. And the demand for clean energy is urgent. Therefore, China and the Gulf States have very good complementarities in energy supply and demand for electricity and energy resources.

There is a need for the long-distance UHV transmission lines between the Gulf States and Sinkiang in the future years. In the case study, the economic benefits of transmission interconnections between the Gulf States and Sinkiang are

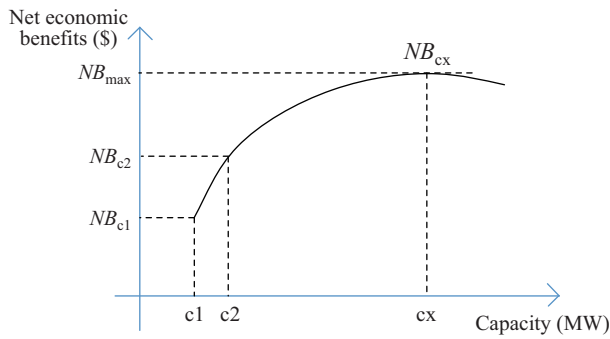


Fig. 4. The relationship between the capacity and net benefits.

assessed on the basis of the proposed model for different transmission alternatives.

The interconnected system between the Gulf States and Sinkiang is established for the year of 2030 in this paper. The data models cover the number and capacity of conventional and renewable generating units respectively, annual chronological load curve of different countries, primary fuel costs and interconnected lines among the interconnected countries. The peak load prediction and installed generation capacity of the Gulf States in the year of 2030 are shown in Table II, which come from national energy report or policy of these countries. The data for the Sinkiang power system is based on the development plan of the “13th Five Year Plan”, where Sinkiang’s electricity delivery capacity will reach 50 million kilowatts by the year of 2020. According to Sinkiang’s clean energy development plans in the future, there will be a total installed generation capacity of 42,000 MW in 2030 including wind power, photovoltaic, and hydropower.

TABLE II
INSTALLED CAPACITY AND LOAD FORECASTING TABLES FOR THE GULF COUNTRIES IN 2030

Countries	Installed capacity [31] (MW)	Annual peak load (MW)	Annual electricity consumption (TWh)
Saudi Arabia	113,448.0	74,136.0 [30]	648.4
Kuwait	27,679.0	25,062.0	114.2
Oman	19,636.0 [36]	14,900.0 [27]	84.8 [27]–[34]
Qatar	18,934.0 [35]	17,141.0 [31]–[35]	81.1 [35]
UAE	52,000.0 [29]	32,800.0 [37]	161.2 [37]
Bahrain	7,341.0 [36]	5,717.0 [28]	21.4 [28]

The annual sequential load profile is obtained by an interpolating method based on the historical winter, summer typical daily load curve, monthly peak load, 2030 peak load and electricity consumption forecast. The load profiles meet the 2030 peak and electricity consumption requirements, such as Kuwait’s annual sequential load profile, as shown in Fig. 5. The primary fuel prices for the Gulf States, including coal, oil, and natural gas, came from the world economic data [32], [33].

According to the research emphasis of this paper, each relevant country can be modeled as a bubble that includes different types of generating resources and electrical load in the simulation. There are no detailed and complex transmission lines inside the bubble. So the multinational interconnected project can be modeled between each bubble. And the bubble

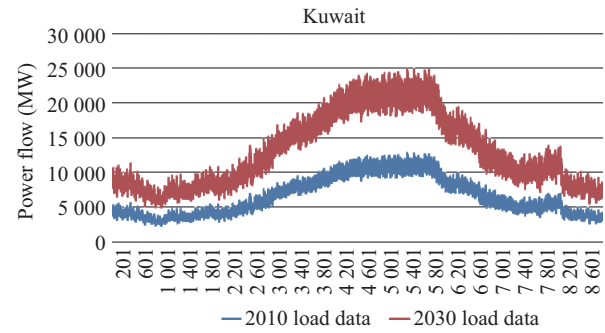


Fig. 5. 2010 and 2030 annual sequential load profile in Kuwait.

model in this paper can be shown as Fig. 6.

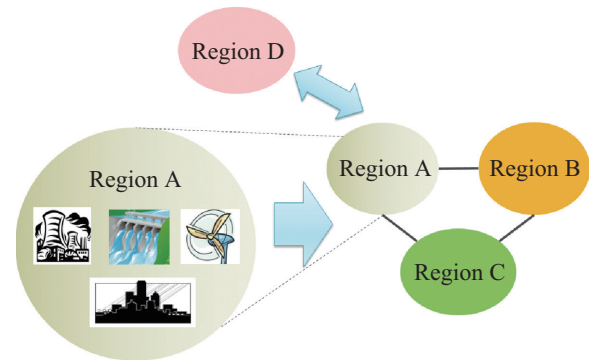


Fig. 6. The bubble model of the simulation.

On the basis of the interconnected status among the Gulf States and the proposed bubble model, Sinkiang can be seen as Region D, and the Gulf States can be seen as Region A, Region B, Region C and so on. Then the simplified interconnection model of multinational interconnected system between the Gulf States and Sinkiang can be shown in Fig. 7.

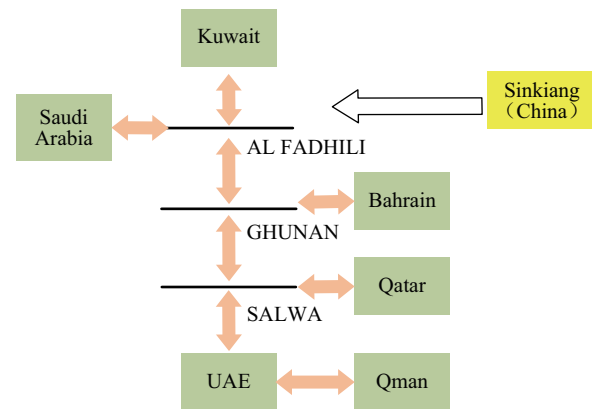


Fig. 7. The interconnected systems between the Gulf States and China.

On the basis of the method put forward in this paper, the chronological simulation for the whole year of 2030 for different planning schemes of the interconnected system are carried out.

B. Results Analysis of China and the Gulf States Interconnected System

When the capacity of an interconnection line is 5 GW, total economic benefits of the load payment and net generation revenue in the interconnected system are shown in Table III. With the interconnected lines, in the year 2030, loads in the total interconnected system pay less by 832 M\$ as a whole. Generation companies in the total interconnected system gain more net generation revenue by 3,799 M\$ as a whole. The total annual benefits due to the interconnected lines is 4,631 M\$.

TABLE III
RESULTS OF CHINA AND THE GULF STATES INTERCONNECTED SYSTEM

	WITHOUT LINK	WITH LINK (5GW)	Benefit (M\$)
Load payment (M\$)	40,538	39,706	832
Generation revenue (M\$)	13,850	17,649	3,799
Total (M\$)			4,631

Considering the costs of the interconnection project, the net benefits are calculated. More cases with incremental transmission capacity are carried out and the corresponding net benefits of different interconnection capacities are shown in Table IV. As we can see from the results, as the transmission capacity increases, the interconnection net benefit increases. The relationship between the different transmission capacities and the benefits is shown in Fig. 8.

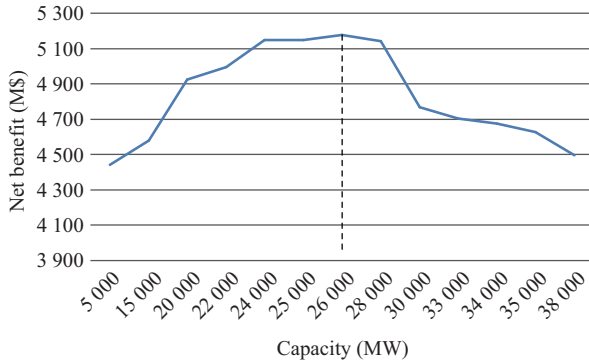


Fig. 8. Results of power grid interconnection between China and Gulf States.

TABLE IV
RESULTS OF CHINA AND THE GULF STATES INTERCONNECTED SYSTEM

Case	Load payment (M\$)	Net generation revenue (M\$)	Capacity (GW)	Cost (M\$)	Net benefit(M\$)
Base case	40,538	13,850			
Case 1	39,706	17,649	5	189	4,441
Case 2	38,305	16,764	15	567	4,580
Case 3	37,633	16,625	20	756	4,924
Case 4	37,821	16,963	22	832	4,997
Case 5	37,524	16,893	24	907	5,150
Case 6	37,402	16,809	25	945	5,149
Case 7	37,529	16,982	26	983	5,158
Case 8	36,978	16,491	28	1,058	5,142
Case 9	36,756	15,970	30	1,134	4,767
Case 10	36,209	15,474	33	1,247	4,705
Case 11	36,204	15,478	34	1,285	4,676
Case 12	36,011	15,273	35	1,323	4,627
Case 13	35,814	15,060	38	1,436	4,498

On the basis of the above calculation results, when the interconnection capacity of Sinkiang to the Gulf States reaches 26 GW, the benefit reaches the maximum at 5,158 M\$. For the optimal case, the power flow of this UHV transmission line is shown in Fig. 9.

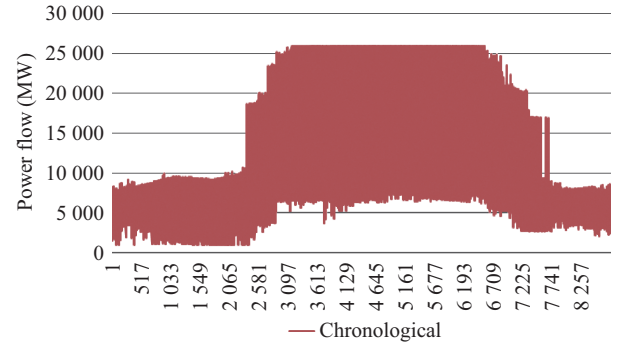


Fig. 9. Power flow of the multinational interconnected lines. Power flow of the multinational interconnected lines.

In Fig. 9 and Fig. 11, the red and blue curves represent the chronological power flow and duration curve, respectively. The overall utilization rate of the transmission link is 49% in terms of total energy transferred on the link. The daily average power flow of the multinational transmission lines is shown in Fig. 10. As we can see from the results, due to the load characteristics of the Gulf countries with high load in summer, the electricity from Sinkiang to the Gulf States plays a role in the daily and seasonal peak shaving, which meets the load demand of the Gulf countries in summer when the transmission is heavily used and even congested.

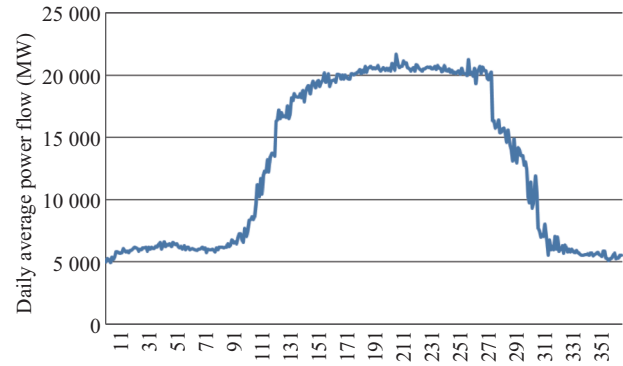


Fig. 10. Daily average power flow of the multinational interconnected lines.

IV. CONCLUSION

In the context of the global energy internet, this paper proposes an economic benefit evaluation model and its application for optimizing transmission capacity for multinational interconnection planning, which can be calculated by using a chronological production cost simulation approach. First, an economic benefit evaluation model is proposed including the overall load payment among the interconnected countries, the net revenues of the generation companies, and the total cost of the interconnection projects. Then, we construct a production

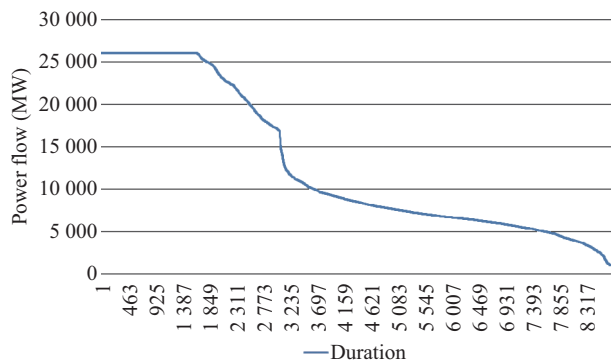


Fig. 11. Utilization level of the multinational transmission lines.

cost simulation model and simulate the chronological operation of the multinational power grid interconnection system by using the model. In the case studies, the interconnected system of the Gulf States and Sinkiang in 2030 has been built. The simulation found the interconnection optimal capacity with the maximum benefit, which demonstrates the feasibility of the proposed method.

The economic cost benefit model proposed in this paper is of great significance to optimize the transmission capacity of the multinational and inter-continental interconnection. This method is suitable for multinational or intercontinental transmission interconnection long-term expansion planning to optimize interconnection capacity in the electricity market environment. Moreover, this method comprehensively takes into account the interests of multiple market entities and aims at maximizing the multiple benefits. And it can provide information to stakeholders to support their decision-making processes.

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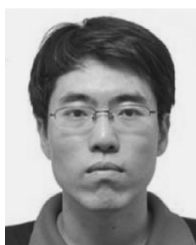
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