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The Efficiency Assessment of Transmission Grid with Massive Clean Energy Based on Production Simulation

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Abstract. As the clean energy developing rapidly in recent years, the operational mode of power system was adjusted persistently because it was impacted by the randomness of clean energy output. Meanwhile, the efficiency of transmission grid was decreasing in certain level for the same reason. The production simulation model of power system was presented, and the power source which considering the output characteristics of different clean energy was described respectively. In additionally, the analytical method of efficiency assessment was proposed to assess the impact degree of clean energy. Moreover, the efficiency index of power transmission system programming was adopted to choose planning scheme. At last, three planning schemes of a power grid with massive clean energy are analyzed to confirm the production simulation model and assessing method.

1 Introduction

With the global climate warming and ecological environment deteriorating seriously, the carbon emission problem becomes more and more concerned in the worldwide. Eventually, in order to protect the climate stable relatively, the utilized of fossil fired energy was controlled orderly all around the world. Therefore, several protocols such as the Paris Climate Accord COP21 have gone into effect. There are two main ways to reduce the carbon emission, one is developing clean energy to take place of traditional fossil energy; another is saving energy to cut down the consumption. After years of effort, the percentage of fossil-fired energy decreased for the 21st century due to renewable energy explosive growth [1]. As report by IEA, in 2016, total combustible fuel plants accounted for 60.8% of total OECD (Organization for Economic Co-operation and Development) gross electricity production (made up of 57.8% from fossil-fuel-fired plants and 3.2% from biofuels, waste, etc. plants), nuclear plants 18.0%, hydroelectric plants 12.9%, and geothermal, solar, wind, tide and other plants at 8.2%. The fossil consumption of China decreased around 320 million tons in 2016. The most important factor about demand falling in China was lower consumption of electricity generation, although China still uses half the world's coal. Alongside the decrease of fossil-fired generation, 2016 also saw the continued increase of renewable generation across the OECD and in countries like China. In the OECD, renewables generation grew by 3.8% to account for 23.8% of all electricity generated, its highest share to date [2]. However, the output of hydroelectric energy and wind energy variate disorderly at any time, the power system operation has been more complicated by massive clean energy increment. Moreover, the power system are required to construct or extend timely to satisfy the new clean energy power accessing to grid, the reasonable power grid planning of clean energy integration ought to consider the security, the efficiency and the social benefit. The tradition power grid planning method estimates the schemes based on a maximum operation mode or minimum operation mode, it cannot reflect the randomness output of clean energy and the influence to other devices. Because of those, a simulation method which is capable to apple to the randomness problem is obliged to be present for evaluate the power grid planning.

The stochastic nature of wind generation increases the fluctuation and the uncertainty on the net load. How well simulation the system running was crucial in analysing the planning scheme. H.T. Yang and S.L. Chen [3] presented a multiobjective optimization approach to generation expansion planning. G. A. Orfanos, P. S. Georgilakis and N. D. Hatziargyriou [4] proposed an efficient approach for probabilistic transmission expansion planning that considers load and wind power generation uncertainties. J. Hargreaves, E. K. Hart, R. Jones, A. Olson [5] outlined a new methodology for modeling the economic tradeoffs in implementing flexibility solutions for integrating renewables. M. Lin [6] presented the results of an investigation of the relative computational speeds and solution qualities of six different probabilistic production cost simulation methods for power systems. W. Wu, Z. Hu etc. [7] proposed a new heuristic methodology for Transmission network expansion planning based on chronological evaluation. A.S.D. Braga, J.T. Saraiva [8] presented a multi-criteria formulation for multiyear dynamic transmission expansion planning problems. F. Bouffard, F. D. Galiana [9] formulated a short-term forward electricity market-clearing problem with stochastic security capable of accounting for non dispatchable and variable wind power generation sources. R. Billinton, W. Wangdee [10].made bulk electric system reliability analysis associated with large-scale wind farms, which assists system planners to create potential transmission reinforcement and schemes to facilitate large-scale wind energy conversion systems additions to a bulk system. Tuohy and O'Malley [11] used Wilmar planning tool which incorporates a stochastic unit commitment model considering reserve for wind and load forecast errors. Ummels et al. [12] relied on the chronological simulation program, PoerSym3, which solves an electricity market-based UC-E model using a heuristic algorithm. Black, et al. [13], [14] developed a methodology that incorporates day-ahead, real-time dispatching, and stochastic sampled power imbalances with reserve allocation. Zhang Ning, et al. [15, [16] describes a chronological production simulation platform and shows how it has been applied to the planning of pumped storage. An important characteristic of these studies is that the simulated system operation day-to-day to be able to capturing the system congestion cost as accurately as possible [17]. The previous studies usually aren't really aware of the efficiency of planning schemes, which is particularly significant which reflects the assets efficiency among different undetermined schemes.

The sequential operation simulation model was established to effectively estimate operation condition of future power system. The model considered load distribution, generator outage and generation dispatch algorithm. Transmission congestion in power system was calculated, the effect of alleviating transmission congestion was analysed. Finally， the efficiency evaluation method of power grid based on improvement was proposed to be used in choose planning scheme..

2 Production simulation model

2.1 Simulation framework

The production simulation framework was used to assess the efficiency of power grid contains seven part, and those was shown in Fig.1. In that, the input-data function is completed in Preparing Data module, the main role of power grid model, load model and source optimization model is to prepare the basic data for Load Flow Calculation module. The efficiency index can be obtained from calculation's results. As a result, the efficiency levels are evaluated by a series of methods, and the different planning schemes are assessed in planning evaluation module by efficiency level and economic.

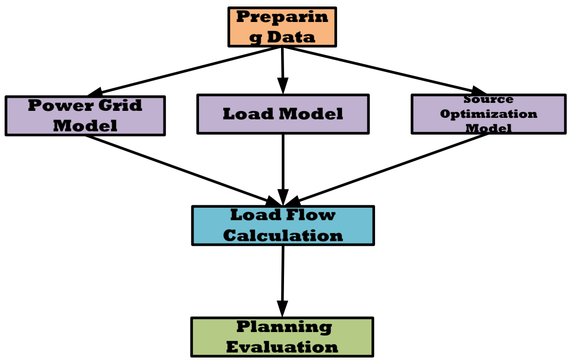


Fig. 1. The framework of production simulation

- Preparing Data

The production simulation requires serval kinds of detail data to describe the power system information. Those might be classified into three types, that is, equipment parameter, operation data and predictive information. In which, the equipment parameter is made up of generations, transforms, transmitting line and the price of each kinds of power; the operation data contains the active power of every lower voltage transformer at each hour in whole year, the hourly wind speed at the wind farm for several years, the hydro energy at every hour of the run-of-river hydroelectric station for several years, the photovoltaic power station output at every hour for several years; the predictive information mainly includes the load growth rate, the installed equipment in planning scheme and the cost of each kinds of power.

- Grid Model

The function of power grid model is constructing the network connection hour-by-hour during the simulation. There are three steps to take shape new connection relation for calculation, the first step is constructing the initial network frame of simulation, the devices have put into operation before simulation date must join to the network frame, the second step updates the network frame hour-by-hour according to the new project's commissioning date during simulation. As often as the new project put into operation, the connection relation adjusts timely based on the system scheme. The above-mentioned new projects cover being constructed and planned. The third step is embodying the maintenance schedule and the operation of power grids, the component during maintenance stage is invalid in network connection, and the equipment arranged as standby application is invalid in network connection. The network frame of every time during simulation is formatted.

- Load model

The fluctuation of the load is expressed in the sum of load from the lower voltage transformers. Therefore, the load model is specific to every lower voltage substation in simulation, and it determines each transformer load characteristic during simulation. The load curve for a transformer might be represented by a sequential array.

For the power grid with N transformers, the load characteristic in whole yare is represented by a matrix P（N, 8760）. The load of power grid is summed by each transformer. But to calculated the planning load distribution, those are divided to operated transformer and planned one, and their formulas are disparate owing to the difference in load growth. For operated transformer, the load characteristic in planning year is almost similar as the one in present, that might increasing in some certain rate according to the development of local economic and society. However, for the new operating transformers, those mainly satisfy the new appeared or existed load in local area. Therefore, the transformer load could calculate as Equation (1) and (2), Equation (1) is for operated transformer and Equation (2) is for new operating transformer.

$$P(\mathrm{u}, j) = P_{now}(\mathrm{u},\ \mathrm{j}) \times (1+v\%)^{(Yp-Ynow-1)} \times n / (n+m(\mathrm{u})+k(\mathrm{u})) \tag{1}$$

In which, P (u, j) is the even load of transformer j at u hour at planning year, v% is the growth rate of electricity consumption in the area of transformer located on, Y_{p} is the planning year, Y_{now} is status year, n is the number of transformers in status year, m (u) is the number of operating transformers under contracture at u hour, k (u) is the number of operating transformers in planning scheme at u hour.

$$P_{p1}(x) = \sum P_{now}(\mathrm{u},\ j) / \mathrm{n} \times (1+v\%)^{(Yp-Ynow-1)} \times (m(\mathrm{u})+k(\mathrm{u}) / (n+m(\mathrm{u})+k(\mathrm{u}) \tag{2}$$

In which, P (u, x) is the even load of transformer x at u hour at planning year, transformer x is the one put into operation in planning year, v% is the growth rate of electricity consumption in the area of transformer located on, Y_{p} is the planning year, Y_{now} is status year, n is the number of transformers in status year, m (u) is the number of operating transformers under contracture at u hour, k (u) is the number of operating transformers at planning scheme at u hour.

Both in Equation (1) and (2), the transformers in equation is lower voltage in power grid. The m (u) and k (u) is related to the simulation times, for example, m (1000) is equal to 3, it represents that there are 3 transformers which is under contracture at present will have put into operation at 1000 hour in simulation year. In other word, m (u) will add 1 until a transformer put into operation at u hours, if there is no transformer start operating at u hour, the m（u） is equal with m(u-1). As a result, the load matrix of every transformer is gained by a series of calculation.

- Generation model

Generally, the generation output should be keep balance to load levels, and it is required keep necessary reserve for power system stable operation. The generation model considers various constraints of different energy. Those are divided into four categories.

1) Gas turbines, it can be stopped and restarted daily and it on/off state is modeled on an hourly basis.
2) Nuclear plants, large thermal unit, and combined heat and power units, those cannot be cycled daily, therefore, they are modeled as being in on/off state at least an entire day.
3) Wind farms, solar plant and run-of-river hydroelectric station, their capacity is determined by the primary energy which can be obtained through long term statistics, and the output be reduced due to minimum load contains or transmission constraints, the reduction can be recorded to reflect the abandoned condition of clean energy. The scholars [18, 19] presented the PV generation character under planning analysis.
4) Hydro units, it has maximum energy constrains and can adjust output hourly, so it is modeled on an hourly basis.

Equations (3)-(9) describe the constrained; the generation's output vectors for every hour in simulation year are calculated by adopting optimization method.

$$Min\sum_{i=1}^{\mathrm{M}} \mathrm{C}(\mathrm{x}_{i,t}) + \sum_{i=1}^{M} s_{it} \tag{3}$$

$$\mathrm{S.\ T.}\ P_{gi,\min} \le x_{i,\ t} \le P_{gi,max} \tag{4}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{M}} x_{di} = \sum_{j=0}^{\mathrm{n+k+m}} P(\mathrm{u},\ \mathrm{j}) \tag{5}$$

$$0 \le x_{i,t} - x_{i-1,t} \le P_{up-i} \ \text{or}\ 0 \le x_{i-1,t} - x_{i,t} \le P_{down\text{-}i} \tag{6}$$

$$\mathrm{T}_{off}(\mathrm{i}) \le \mathrm{t}_{t-off,i} \tag{7}$$

$$\mathrm{T}_{on}(\mathrm{i}) \le \mathrm{t}_{t-on,i} \tag{8}$$

$$\mathrm{x}_{\mathrm{i},\ \mathrm{t}} = 0,\ \mathrm{t} \in (\mathrm{U}_{1\mathrm{i}},\ \mathrm{U}_{2\mathrm{i}}) \tag{9}$$

$$-S_m \le \sum_{c=1}^{\mathrm{w}} GSDF_{c,m} \times x_{i,t} + \sum_{d=1}^{z} LSDF_{d,m} \times P_{b,t} \le S_m \tag{10}$$

The objective is the minimization of the total system operation cost, shown in Equation (3)，it mainly includes start-stop and generating fuel cost C($x_{\mathrm{i,t}}$) is the generation fuel cost with the output vector being $x_{\mathrm{i,t}}$, the $\mathrm{s}_{\mathrm{i,t}}$ is the start-stop cost under those circumstance. Equation (4) enforce the limits on output of each generator, $P_{\mathrm{gi},max}$ and $P_{\mathrm{gi},\ max}$ are the maximum output of the generation and the minimum one. Equation (5) represents the load-generation balance constrain, the x_{di} is the output of generator, $P(u,j)$ is the load of transformer j. Equation (6) enforces the generation ramp rate limits, $P_{\mathrm{up\text{-}i}}$ and $P_{\mathrm{down\text{-}i}}$ is the positive ramp limit and negative one respectively. Equation (7) and (8) define the states of the generators as discrete variables, T_{off}(i) and T_{on}(i) is the least time of generation i. Equation (9) enforce the maintenance state of generator, ($U_{1\mathrm{i}}$,$U_{2\mathrm{i}}$）represents the maintenance time of generation i. Equation (10) represents the restrain of power grid, S is the limit capacity of branch m included transmission line and transformer, $GSDF_{\mathrm{c,m}}$ is the generation shifted distribution factor of branch m, and $LSDF_{\mathrm{d,m}}$ is the load shifted distribution factor of branch m, $\mathrm{x}_{\mathrm{i,t}}$ is the output of generation i at t hour, $P_{\mathrm{b,t}}$ is the load of substation b at t hour. Ultimately, the units output vector are optimized for calculation.

- Load flow model

The load flow model adopts the DC-flow method based on network frame, load matrix and units output vector being known, the load flow of every device in power grid is gained through DC-load flow calculations.

- Planning scheme evolution

A series of indexes for evaluating contains efficiency and benefit of the proposed planning scheme through power system production simulation. The efficiency index includes the utilization ratio of facility, which is about transformer and transmission line, the heavy load proportion of facility, and the light load proportion of that; the benefit indexes comprises cost of power supply, line loss, and abandon clean energy. The evaluation method for power system planning schemes is improvement comparing the planning scheme and present levels, in other words, the recommend scheme must be the one with the highest improvement.

2.2 Simulation process

The power system production simulation process is built for assessing the efficiency of planning scheme, as illustrated diagrammatically in Fig.2. After setting times and preparing data, the necessary elements to simulation are provided on account of proposed model in section 2.1. Then, the calculation is executed according to simulation times, the simulation adopted the DC-flow method based on network frame, load matrix and units output vector which being known by corresponding model, the efficiency indexes is gained through the load flow of every device in power grid from simulation.

The electric Power System Production Simulation Station (EPSPST 1.0) was developed by ourselves, which was adopted VC programming and matrix computing library.

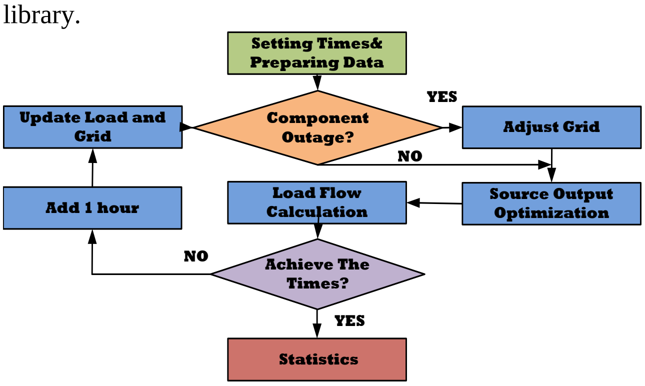


Fig. 2. The process of production simulation

3 Experimental situation

3.1 Abbreviations and acronyms

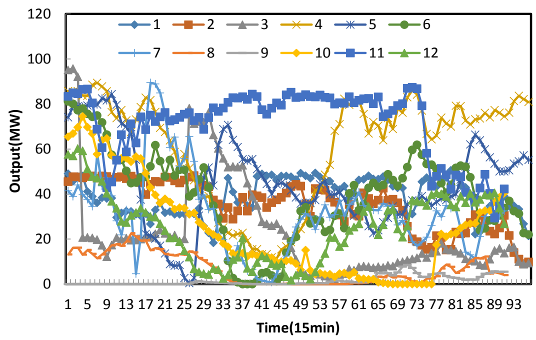
Tanggu distinct in Tianjing power grid is used as an experimental example to confirm the practicability of production simulation model in this paper. The power grid was made up of two 220kV substations of with 5 transformers and ten 110kV substations with twenty two transformers, six 220kV transmission lines and thirty nine 110kV transmission lines in system until 2017. Meanwhile, two 110kV projects are under construction or in the plan. To 2020, those includes one 220kV substation with two transformers, two 110kV substation with five transformers, three 220kV transmission lines and twelve 110kV transmission lines would put into operation. The raw data is the statistical results from actual running data and simulation data，and the index calculation ways was introduced in our previous study [20].The efficiency index of the present-day power grid is lied out in Table.1.

Table 1. The efficiency index of present-day power grid.

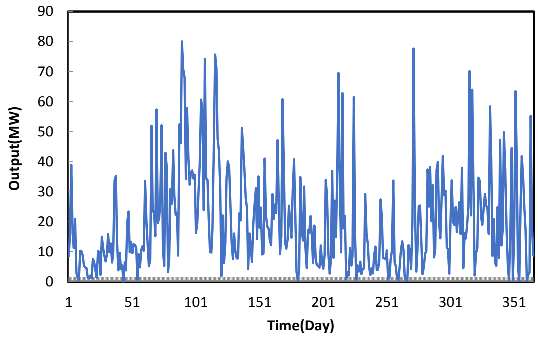
Index	**110kV**	**220kV**
Utilization ratio of Tran	25.5%	27.6%
Heavy load proportion of Tran	1.2%	0.45%
Light load proportion of Tran	5.2%	4.2%
Utilization ratio of Line	30.6%	24.3%
Heavy load proportion of Line	1.1%	0.34%
Light load proportion of Line	6.1%	4.5%
Cost of power supply(g/kWh)	305	
Line loss	1.4%	
Abandon clean energy proportion	1.5%	

3.2 Generation

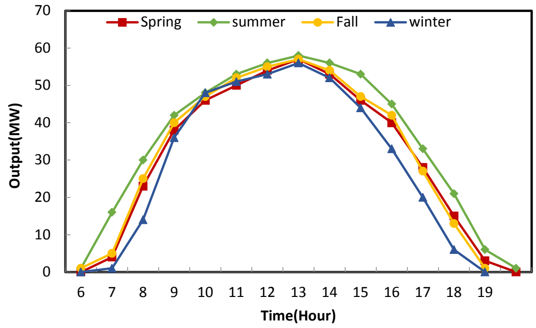
Nowadays, two 220kV thermal power plants contained 300MW coal-fired, 600MW gas-fired and 300 MW hydro plant in power grid, a 50MW wind plant that connect to 110kV power grid through step-up transformer. At the same time, a PV plant is planned to operation at 2020. Moreover, there are two 120MW wind plants and another 60MW PV plant is suggested to construct in planning phase, the wind output and solar irradiation characteristic curves are shown in Fig.3, in which, the typical wind plant output in one day of each month is shown in Fig.3 (a), the average day output of wind plant in a year is shown in Fig.3 (b), and the PV plant output is shown in Fig.3 (c) and (d).



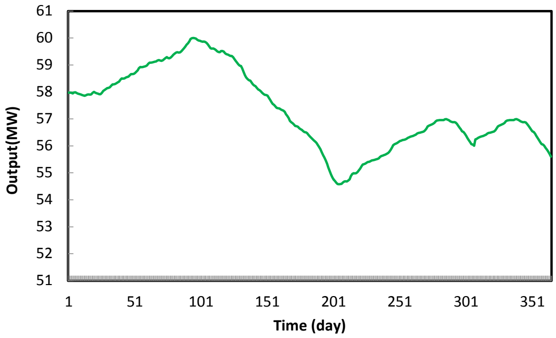
(a)



(b)



(c)

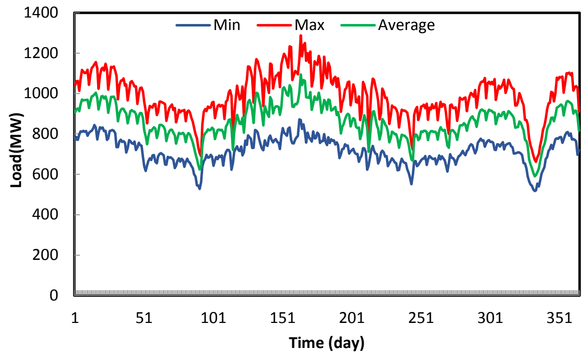


(d)

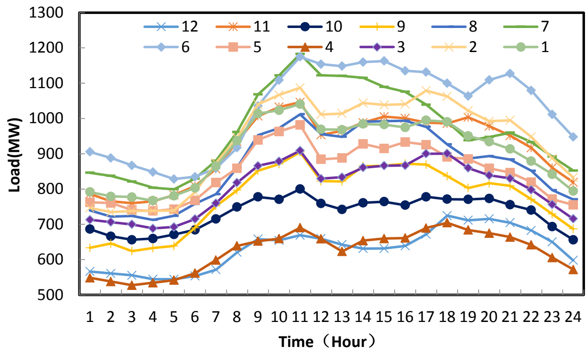
Fig. 3. The typical continuous output of wind plants (a, b) and PV plant (c, d) in the district.

3.3 Load

The total load of 110kV step-down transformers is 1090MW and the electrical power of that were 51 billion kilowatt hours in 2017. The total load and electrical power of every transformer is forecasted according the requirement of that area. The average increment rate of the consumption is about 3% per year. The load curves of the power grid at last year are shown in Fig.4, in which, the average load, maximum load and minimum load of everyday in a year is shown in Fig.4 (a), and the typical day-load curves of each month is shown in Fig.4 (b).



(a)



(b)

Fig. 4. The load curves of a whole year. (a) and a day (b)

3.4 Planning schemes

In the next two year, totally 300MW clean energy will connect into power grid. For that, three planning schemes to access to the clean energy were proposed, that named as A, B and C. the scheme A was building four 110kV step-up substation respectively and connect into neighboring 110kV substation with each 110 kV transmission line. The scheme B was constructing one 220kV step-up substation and two 110kV step-up substations and access to nearby substation. The scheme C was established two 220kV step-up substations and those transmission lines, the schematic diagram of 3 planning schemes was shown in Fig.5.

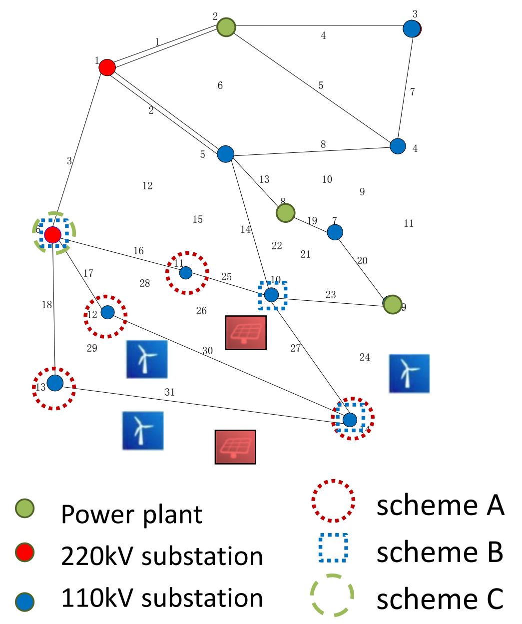


Fig. 5. The Schematic diagram of 3 planning schemes

4 Results analysis

4.1 Results

After simulating throughout of the model presented in section two, the load data at each hour of three power grid planning schemes were obtained, the efficiency results could be calculated throughout the production simulation process, the indexes of efficiency of each scheme list in Table.2. Since the clean energy increasing in power system, the power supply fluctuated randomly which caused to the load flow undulate correspondingly. As a result, the utilization ratio of the transmission line decreased in some sense compared to present efficiency, the heavy-load proportion and light-load one increased as a whole, but the index level of transformer fluctuated within a certain range; the cost of power supply came down rapidly for mass clean energy development, the abandon clean energy were different among three schemes.

Table 2. The efficiency index of planning power grid.

Index	110kV	220kV	110kV	220kV	110kV	220kV
Utilization ratio of Tran	22.5%	28.1%	26.2%	25.2%	23.8%	26.6%
Heavy load proportion of Tran	1.7%	0.56%	1.4%	0.49%	1.5%	0.52%
Light load proportion of Tran	9.1%	3.7%	5.7%	4.5%	5.9%	4.1%
Utilization ratio of Line	28.2%	25.1%	31.2%	23.1%	29.4%	24.2%
Heavy load proportion of Line	1.8%	0.43%	1.5%	0.76%	1.7%	0.53%
Light load proportion of Line	8.1%	4.1%	7.5%	6.5%	7.8%	5.4%
Cost of power supply(g/kWh)	241		242		243	
Line loss	1.4%		1.5%		1.5%	
Abandon clean energy proportion	2.1%		2.1%		2.1%	

4.2 Efficiency analysis

The comprehensive effect indicator of each scheme is proposed to reflect the improvement in terms of efficiency. It is accessed through comparing the indexes between the planning scheme and present. The formula is shown as Equation (11).

$$E_{ff} = \sum_{i=1}^{d} u_i Q_h(i) = \sum_{i=1}^{d} u_i \left[(k_{h-i} - k_{h-n}) / k_{h-n} \right] \quad (11)$$

In which, E_{ff} is the comprehensive effect indicator, Q_i is the improvement of index i which belong to the efficiency indexes in section 2.4, u is the weighting coefficient which is shown in Table.3 depending on the significance of index, k_{h-n} is the index of present grid, k_{h-I} the index of planning grid.

The results of each scheme is shown in Table.3, the E_{ff} of scheme A, B and C is positive number, it means that the comprehensive effect of those planning schemes improves compared with present one. As a result, the indicator of scheme C is maximum based on calculation, the mainly effect of scheme C is the utilization ratio and extreme efficiency ratio proportion which precedes others.

Table 3. The comprehensive effect indicator of each scheme.

Index	*u*	Scheme A	Scheme B	Scheme C
Q_1_Utilization ratio of Tran	0.5	-0.024	-0.016	-0.025
Q_2_Heavy load proportion of Tran	-0.3	-0.111	-0.044	-0.067
Q_3_Light load proportion of Tran	-0.3	-0.109	-0.026	-0.019
Q_4_Utilization ratio of Line	0.5	-0.015	-0.005	-0.012
Q_5_Heavy load proportion of Line	-0.3	-0.165	-0.171	-0.165
Q_6_Light load proportion of Line	-0.3	-0.045	-0.096	-0.074
Q_7_Cost of power supply(g/kWh)	-5	1.049	1.016	1.033
Q_8_Line loss	-0.5	-0.011	-0.036	-0.036
Q_9_Abandon clean energy proportion	-1	-0.400	-0.400	-0.400
E_{ff}		0.171	0.223	0.235

5 Conclusions

The efficiency of power system is closely related to the power system scale, wind plant installed capacity and the load characteristic. A production simulation model is proposed which considered those factors in power system, which includes load model, generation model, power grid model and operation scheduling. The simulation process is established to emulate the power system operation for whole year. The studied method is capable to figure out the operation condition of a planning power system rely on the current operating data, project-to-be durations and planning forecast data. The efficient indexes contains load ratio, heavy/light load proportion and generating cost, those are calculated from the simulation results, moreover, the comprehensive effect indicator is established to reflect the variation between present power grid and planning one, it could be used to access improvement the planning scheme. At last, three power grid plans to develop massive clean energy in following year, the impact of clean energy development is demonstrated by assessing the efficiency through product simulation.

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