A time sequential simulation method for monthly energy trade planning in the power system with multiple energy resources

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Abstract. The mathematical model of power scheduling in the power systems containing many kinds of energy resources is very complex, for it involves many variables, which result in long solving time and high computation requirement especially in the medium-long time scale planning. The existing monthly energy trade planning methods usually focus on single conventional power energy resource. Therefore, it is difficult to effectively deal with the problem of monthly trading plan with multiple energy sources. To solve the problem above, a new time sequential simulation method is proposed. The method presented in this paper takes into account the output characteristics of renewable energy, the output characteristics of conventional units, load characteristics, peak load regulation characteristics of units, and the operation mode. A novel monthly trading planning model which can satisfy the energy saving generation dispatch is presented and is solved using the presented time sequential simulation method by which the power operation is optimized time interval by time interval. The simulation results verify that the presented model and solving method is reasonable and effective. The comprehensive generation costs can be reduced and the social benefits can be improved by using the presented model and method in the process of monthly planning.

1. Introduction

Monthly energy trade planning is one of the most important work for energy trade center. Whether the monthly trading planning is appropriate will directly influence the daily dispatching economy and security, and it will also impact the profit of generating company and the power grid company. If the annual contract energy plan for each generating company cannot be resolved appropriately into monthly energy planning, the annual contract might not be finished, which could be measured according to the stipulation that the annual contract energy execution deviations should be less than 2% in China. According to the national energy saving generation dispatching approach [1] and the principles of economy and energy conservation, the renewable power generation should be scheduled preferentially, on the premise of system operation reliability and security. The peak regulation capacity should be increased so that the renewable resources, for example wind power, could be used as much as possible. In general, hydro power, pumped storage units and coal-fired units with regulation ability are the first choices for peak regulation. And other kinds of generating units, such as nuclear units, are the second choices for meeting peak regulation requirement. And then if necessary,
thermal units would be demanded to participate in the severe peak regulation and peak-load-dispatching.

There have been many researches on the short-term (daily) generation scheduling [2-4] and long-term(yearly) trading planning [5-6]. However, the studies on the mid-term (monthly) energy trade planning has been relatively scarce, and the present studies has not constructed a unified model [7-8]. Especially for the monthly energy trade planning which consider the factors of multiple power supply, energy saving and emission reduction, and as same as operation economy, the study is in the starting stage. The approach that averagely allocates the annual electricity energy to monthly energy trade planning is usually applied in provincial energy trade center, which is rather simple but extensive. And when using the averagely allocating method, other energy sources such as wind power and nuclear power are usually unconsidered, which result in large deviation with actual operation situation and wasting of resources.

Monthly energy trade planning with conventional energy sources was studied in [7] and [8]. A load ratio deflection method was used in [7] to deal with the trading plan of directly dispatched thermal power generation units. Based on the multi-target synthetical arrangement results, units’ trading schedule of partial units would be adjusted within the constraint of load rate deviation adjustment. A monthly method was proposed to decompose the annual contract electricity of a hydro power station in [8]. The quantitative relationship between competitive profit and risk in monthly trading market is determined by establishing an annual contract decomposition model which maximizes the profit of monthly trading market. It lays the foundation for the monthly trading plan of hydropower units. However, methods proposed in [7] and [8] only focus on single conventional energy source and are unable to effectively deal with the condition of monthly electricity trading plan with multiple energy sources.

A monthly energy trade planning model is presented in this paper according to the energy saving generation dispatching which realizes the goal of scientifically and rationally arranging the grid operation mode. Multiple power sources are considered in the proposed model, which means that the mathematical model is sophisticated but complex and involves many variables. Thanks for the condition that the existing computer processing capabilities and methods have been greatly improved, the time sequential simulation method can be introduced to deal the scheduling problem with longer time scales. In this paper, the time sequential simulation is introduced to deal with the problem of monthly energy trading planning with multiple energy sources, including wind power, nuclear power, hydro power and thermal power.

For the obvious randomness and volatility of natural wind, the wind power has high uncertainty. The proposed time sequential simulation takes many factors into account, such as various energy output characteristics, load characteristics, peak load regulation characteristics and start-up modes, to maintain the real-time balance between load and generation of multiple power sources.

2. Time sequential simulation and energy saving generation dispatching

2.1. Time sequential simulation
Time sequential production simulation plays an important role in the operation and decision-making of power system [9]. The time scale of short-term simulation is usually several hours to dozens of hours. It can provide real scenario simulation for optimizing the system operation mode and improving the balancing ability of wind and hydropower power. It can also provide reasonable generation plan for the dispatching department. The time scale of long-term simulation can be several months to years. It can simulate the annual balance of wind and hydro power under different situations of installation capacity and power grid structure. Time sequential simulation has been widely applied to power balancing and scheduling of generation production. Because all the time scales including annual, monthly and daily wind power output changes are larger, for better reflecting wind power variation characteristics and comprehensively considering the wind power balance problem, the time sequential
production simulation method is introduced to establish a monthly energy trade planning model with various energy sources including wind, nuclear, hydro and thermal power in this paper.

2.2. Energy saving generation dispatching

Energy saving generation dispatching is a generation dispatching rule based on the purpose of energy saving and emission reduction. It is the institutional change of the original dispatching mode (according to the average distribution of generating hours by the unit capacity) on the basis of the traditional dispatching mode of equal incremental coal consumption for power supply. The aim is to establish a power dispatching mode based on the level of energy consumption and pollutant emission. The approach is to maximize the function of renewable and other clean energy sources so as to reduce the use of fossil fuels under the premise of ensuring the safety and reliability of power grid. The energy saving generation dispatching is applicable to the whole generators in the grid. After the implementation of energy saving generation dispatching, it will give priority to renewable energy units. In this case, the generation output of power units with high pollution and high energy consumption will be decreased. When establishing the dispatching mathematical model, the generation costs of wind, hydro and nuclear power are usually neglected.

3. Mathematical model

As for making the monthly energy trade plan that integrates various energy sources including wind, nuclear, hydro and thermal energy, and meeting the requirements of energy saving generation dispatching, a monthly trading planning method based on time sequential simulation is proposed in this paper. According to the presented method, the operation status of each generating unit and regards system load, wind power and other units’ output was simulated as time-series changing with time based on the prediction sequence of load and wind power output. The balance between system load and units’ output is taken as the balancing constraints. The optimal unit output index can be obtained. The objective of the models to minimize the total cost in the whole month. And the constraints include unit output constraints, system balance constraints, power grid peak shaving capability constraints, and system reserve constraints, etc. In practical applications, some constraints can be dynamically adjusted according to the actual power grid conditions.

3.1. Objective function

To reduce the monthly comprehensive cost of generation, the objective function of monthly energy trade planning with multiple energy resources can be expressed as:

$$F = \min \sum_{i=1}^{N_t} ((\sum_{i=1}^{N_p} (a_i P_{Ti}^2 + b_i P_{Ti} + c_i + m_{Ti} \Delta P_{Ti}^u + S_{Ti} u_i' (1-u_i'^{-1})) + \sum_{k=1}^{N_n} (P_{Tn}^{max} - P_{Tn}) m_{nk} )$$

(1)

where i and k are respectively the labels of thermal and nuclear power units. $N_t$ and $N_n$ are respectively the total numbers of thermal and nuclear power units. $a_i$, $b_i$ and $c_i$ are fuel cost coefficients of thermal unit $i$. $P_{Ti}^u$ is the output of thermal unit $i$ at the time interval $t$. $m_{Ti}$ is the peak regulation cost of unit $i$. $\Delta P_{Ti}^u$ is the paid peak regulation of thermal unit $i$ at the time of $t$. $S_{Ti}$ is start-up cost of thermal unit $i$. $u_i'$ and $u_i'^{-1}$ are respectively the status of thermal unit $i$ at the time of $t$ and $t-1$; $u_i'^{-1}=1$ and $u_i'=0$ respectively represent the working and outage status; $P_{Tn}^{max}$ is the maximum output of nuclear unit $k$; $P_{Tn}$ is output of nuclear unit $k$ at the time of $t$; $m_{nk}$ the peak regulation cost of unit $k$.

The objective function is to minimize the monthly comprehensive costs of generation. Four parts compose the comprehensive costs. The first part is the generation cost of the thermal units. The second part is the peak regulation cost of the thermal units. The third part it the start-up cost of the thermal units. And the forth part is the peak regulation costs of the nuclear units.
3.2. Constraints

1) Constraints for wind power units:

\[
0 \leq P_w^t \leq P_w^{\ast}
\]

where \( P_w^t \) is the wind output actually accepted by the grid; \( P_w^{\ast} \) is predicted wind power output.

2) Constraints for nuclear power units [10]:

\[
\begin{align*}
u_k' + u_k' &= 1 \\
P_k^t &= P_k^{\text{max}} \\
P_k' &= P_k^{\text{min}} \\
u_k' &= \max\{u_k', u_k'\} \\
P_k' &= \max\{P_{k_1}^t, P_{k_2}^t\} \\
(u_k' - u_k'^{-1})(X_{n_{w,k}}^{t-1} - T_{\text{low,k}}) &\leq 0
\end{align*}
\]

In the equations, the nuclear unit \( k \) is replaced by two virtual units \( k_1 \) and \( k_2 \). They respectively represent the rated operation mode and “15-1-7-1” decreasing operation mode. Under the “15-1-7-1” decreasing mode, the continuous operation with rated output is for 15h. Then the generation output of nuclear units will be gently decreased in 1h and operate with 60% of rated output for 7h. At last, the output will be gently increased in 1h. \( P_{k_1}^t \) and \( P_{k_2}^t \) are respectively the outputs of two virtual units \( k_1 \) and \( k_2 \) at the time of \( t \). \( P_{k_{\text{min}}}^t \) is the lower limit of nuclear unit output under the condition of decreasing operation. \( X_{n_{w,k}}^{t-1} \) is the continuous starting time of nuclear unit \( k \) until the time of \( t-1 \). \( T_{\text{low,k}} \) is the number of intervals in the “15-1-7-1” decreasing mode.

Equation (3) requires that nuclear units must operate in one of the two modes. Equation (4) and (5) express that \( k_1 \) and \( k_2 \) respectively represent the rated and decreasing mode. Equation (6) guarantees nuclear units would not shut down. Equation (7) shows that nuclear unit works based on the bigger of the two virtual units’ outputs. Equation (8) is the constraint time of decreasing output. In the “15-1-7-1” mode, decreasing duration is 7h. If the remaining time is less than 7h, the decreasing process should be kept.

3) Constraints for hydro power units [11]

\[
\begin{align*}
V_m^{t+1} &= V_m^t + f_m^t - q_m' \\
V_m^{t+1}_\text{min} &\leq V_m^t \leq V_m^{t+1}_\text{max} \\
q_m^{t+1}_\text{min} &\leq q_m^t \leq q_m^{t+1}_\text{max} \\
P_{\text{water}}^{t+1}_\text{min} &\leq P_{\text{water}}^t \leq P_{\text{water}}^{t+1}_\text{max}
\end{align*}
\]

where \( m \) is the label of hydro power station; \( N_{\text{water}} \) is the total number of hydro power stations; \( V_m^t \) and \( V_m^{t+1} \) are respectively reservoirs of hydro station \( m \) at the time of \( t \) and \( t+1 \). \( f_m^t \) is the inflow of hydro station \( m \) at the time of \( t \). \( q_m^t \) is the used flow for generation of hydro station \( m \) at time \( t \). \( V_m^{t+1}_\text{min} \) and \( V_m^{t+1}_\text{max} \) are respectively the minimum and maximum allowable reservoir of hydro station \( m \). \( q_m^{t+1}_\text{min} \) and \( q_m^{t+1}_\text{max} \) are respectively the minimum and maximum allowable let-down flow. \( P_{\text{water}}^{t+1}_\text{min} \) and \( P_{\text{water}}^{t+1}_\text{max} \) are respectively the minimum and maximum allowable output; \( a \) is the output coefficient of hydro station \( m \); \( h_m' \) is the average water head of hydro station \( m \) at time \( t \).
Equation (9) is the constraint for water balance. Equation (10) is the constraint for reservoir capacity of hydro power station. Equation (11) is the constraint for hydro flow. Equation (12) is the constraint for output range of hydro station.

4) Constraints for the pumped storage power station [12]

\[ P^\text{i}_{j} = P^\text{max}_{j} \]  \hspace{1cm} (13)

\[ u'_j + u''_j \leq 1 \]  \hspace{1cm} (14)

\[ \sum_{j=1}^{N_c} P^\text{max}_{c_j} - \sum_{j=1}^{N_c} P^\text{i}_{c_j} \leq W' - W_i \]  \hspace{1cm} (15)

\[ W_i \leq W_0 + \mu \sum_{i=0}^{t} P^\text{i}_i - \sum_{i=0}^{t} P^\text{p}_i \leq W_u \]  \hspace{1cm} (16)

\[ \mu \sum_{i=0}^{t} P^\text{i}_i - \sum_{i=0}^{t} P^\text{p}_i = 0 \]  \hspace{1cm} (17)

where \( j \) is the label of pumped storage station; \( N_c \) is the total number of pumped storage stations; The station \( j \) is equal to two virtual units \( g_j \) and \( c_j \). They respectively represent the generation and pumping condition. \( P^\text{g}_i \) and \( P^\text{c}_i \) are respectively the output at the time of \( t \) under the two different conditions. \( u'_j \) and \( u''_j \) respectively represent the conditions of virtual units \( g_j \) and \( c_j \). \( W_i \) and \( W_u \) are respectively the upper and lower limit of reservoir capacity. \( W_0 \) is the initial reservoir capacity; \( \mu \) is the efficiency of pumped storage station. It should be noted that \( W_u \), \( W_i \) and \( W_0 \) have been translated from water to corresponding power.

Equation (13) shows that full power operation should be maintained under the pumping condition. Equation (14) shows that pumped storage station cannot generate and pump at the same time. Equation (15) shows that pumped storage stations should have the ability to provide spinning reserve under the constraint of storage capacity. Equation (16) is the constraint of reservoir capacity. Equation (17) is the constraint of balance from the beginning to the end of the dispatching.

5) Constraints for thermal power units

\[ u'_j \text{min} \leq P^\text{i}_j \leq u'_j \text{max} \]  \hspace{1cm} (18)

\[ -\Delta P^\text{dow}_{T_j} \times T_{60} \leq P^\text{i}_j - P^\text{p}_j \leq \Delta P^\text{up}_{T_j} \times T_{60} \]  \hspace{1cm} (19)

\[ (u'_{j,\text{off}} - u'_{j,\text{on}})(X''_{j,\text{off}} - X''_{j,\text{on}}) \leq 0 \]  \hspace{1cm} (20)

\[ (u''_{j,\text{off}} - u''_{j,\text{on}})(X''''_{j,\text{off}} - X''''_{j,\text{on}}) \leq 0 \]  \hspace{1cm} (21)

When taking into account the deep peak regulation, the equations below should be meet,

\[ P^\text{min}_{T_j} \leq P^\text{i}_j \leq P^\text{max}_{T_j} \]  \hspace{1cm} (22)

\[ \Delta P^\text{d}_{T_j} = \begin{cases} P^\text{max}_{T_j} - P^\text{i}_j & P^\text{min}_{T_j} > P^\text{i}_j \\ 0 & P^\text{min}_{T_j} \leq P^\text{i}_j \end{cases} \]  \hspace{1cm} (23)

where \( P^\text{max}_{T_j} \) and \( P^\text{min}_{T_j} \) are respectively the upper and lower limits for units output ; \( \Delta P^\text{up}_{T_j} \) and \( \Delta P^\text{dow}_{T_j} \) are respectively the upper and lower climbing rates; \( T_{60} \) is the operation interval, which is 60 min in this paper. \( X''_{j,\text{off}} \) and \( X''_{j,\text{on}} \) respectively the starting and down time until the interval of \( t-1 \). \( T_{\text{on},j} \) and \( T_{\text{off},j} \) are respectively the minimum starting and down time. \( P^\text{max}_{T_j} \) is the minimum output of thermal unit with deep peak regulation.

Equation (18) is the constraint for units output; Equation (19) is the constraint for climbing rate; Equation (20) and (21) are the constraints for minimum on and off time; Equation (22) and (23) are the constraints for paid peak regulation power.

6) System constraints
\[
\sum_{i=1}^{N_g} P^r_{i,j} + \sum_{m=1}^{N_g} P^r_{m,j} + \sum_{j=1}^{N_g} P^r_{j} + P^r_w = \sum_{j=1}^{N_g} P^r_{j} + P^r_w \quad (24)
\]

\[
R^r_u = \sum_{i=1}^{N_g} R^r_{i,j} + \sum_{m=1}^{N_g} R^r_{m,j} = \sum_{j=1}^{N_g} R^r_{j} - P^r_{w,u} \quad (25)
\]

\[
R^r_{i,j} = \min(P^r_{i,j} \text{max} - P^r_{i,j} \text{min}, T_{10} \times \Delta P^p_{i,j})
\]

\[
P^r_{i,j} \text{max} = \text{min}(P^r_{i,j} \text{max} + P^r_{i,j} \text{max} + \Delta P^p_{i,j} \times T_{10})
\]

\[
R^r_{i,j} = P^r_{i,j} \text{max} - P^r_{i,j} \text{min}
\]

\[
R^r_{i,j} = P^r_{i,j} \text{max} - P^r_{i,j} \text{min}
\]

\[
\sum_{i=1}^{N_g} R^r_{i,j} + \sum_{m=1}^{N_g} R^r_{m,j} + \sum_{j=1}^{N_g} R^r_{j} \geq (P^r_{i,j} - P^r_{i,j}) \times W^r_{d,u}
\]

\[
R^r_{i,j} = \min(P^r_{i,j} - P^r_{i,j} \text{min}, T_{10} \times \Delta P^p_{i,j})
\]

\[
P^r_{i,j} \text{max} = \text{max}(P^r_{i,j} \text{min} - P^r_{i,j} \text{max} - \Delta P^p_{i,j} \times T_{10})
\]

\[
R^r_{i,j} = P^r_{i,j} \text{max} - P^r_{i,j} \text{min}
\]

\[
R^r_{i,j} = P^r_{i,j} \text{max} - P^r_{i,j} \text{min}
\]

where \( P^r_i \) is the system total load; \( R^r_i \) and \( R^r_n \) are respectively the total positive and negative provided spinning reserve at the time of \( t \). \( R^r_{i,j} \) and \( R^r_{n,j} \) are respectively the positive and negative provided 10-min spinning reserve by thermal unit \( i \). \( R^r_{i,j} \text{max} \) and \( R^r_{n,j} \) are respectively the positive and negative spinning reserve by hydro unit \( m \) at the time of \( t \). \( R^r_{i,j} \) and \( R^r_{n,j} \) are respectively the positive and negative provided spinning reserve by pumped storage unit \( j \) at the time of \( t \). \( L\% \) is the requirement for positive spinning reserve considering load forecasting error; \( W^r_{u,u} \% \) and \( W^r_{d,u} \% \) are respectively the requirement for positive and negative spinning reserve considering forecasting error of wind power. \( P^r_{i,j} \text{max} \) and \( P^r_{i,j} \) are respectively the maximum and minimum output of thermal unit \( i \) at the time of \( t \). \( T_{10} \) is the response time of spinning reserve, which is set as 10 minutes.

Equation (24) is the constraint for active power balance. Equation from (25) to (29) are constraints for positive spinning reserve. Equation from (30) to (34) are constraints for negative spinning reserve.

7) Constraints for energy contract

\[
1 - \eta \leq \frac{W_{r,c}}{W_{r,c}} \leq 1 + \eta
\]

\[
1 - \eta \leq \frac{W_{w,mc}}{W_{w,mc}} \leq 1 + \eta
\]

where \( W_{r,c} \) and \( W_{w,mc} \) are respectively the daily generation schedules of thermal unit \( i \) and hydro unit \( m \) in month \( e \). \( W_{r,c} \) and \( W_{w,mc} \) are daily decomposition value of annual contract energy of thermal unit \( i \) and hydro unit \( m \) in month \( e \). \( \eta \) is the load ratio deflection.

Equation (35) and (36) are respectively the constraints for completion progress of contract energy of thermal and hydro units.

By solving the optimization problem with the comprehensive objective function (1) and constraints from (2) to (36), monthly energy trade schedule considering multiple resources can be obtained based on time sequential simulation method.
4. Simulation results

4.1. Test system

In the test system there are 10 thermal units, 1 pumped storage power station, 1 nuclear power station, 1 hydro power station and 1 wind power station participating in the formulation of the monthly power transaction plan. The selected month is July. Figure 1 shows the contract energy data of the units. Figure 2 and figure 3 respectively show the distribution of annual and July load coefficient. The maximum output of nuclear units is 200MW. It is 70$ per peak regulation.

![Figure 1. Contract energy data of traditional units.](image1)

![Figure 2. Annual load coefficient.](image2)

![Figure 3. Load coefficient in July.](image3)

1) The power load

The load in July is obtained by load forecasting. The simulation step is 1h. There are 744 time intervals in one month, which is shown in figure 4.

2) Wind power output

The output of wind power in July is obtained by forecasting, which is shown in figure 5.

![Figure 4. Load level.](image4)

![Figure 5. Time sequential series of wind power output.](image5)

4.2. Test results

The decomposition values of monthly energy for all the units based on time sequential simulation are shown in figure 6. In addition, the results of average decomposition method are also shown in the figure.

It can be found from figure 6 that the total energy planning of thermal units is 995121MWh, which is lower than the result using the average decomposition method by 20308MWh. However, the generated energy results of hydro and wind power units are obviously higher than the results using average decomposition method. Because the nuclear power unit only has two modes of output and the condition of decreasing force is much difficult to meet, it is always in full capacity operation. In addition, the peak regulation ability of pumped storage power station is also taken into account using
the time sequential simulation method. The energy planning of pumped storage power station is 11690MWh in July and the pumping energy is 14600MWh. The monthly comprehensive cost of generation based on time sequential simulation is 23923541$, which is less than the result using average decomposition method by 489460$. The monthly energy trade plan in July is shown in figure 7.

The energy trade planning of each unit in the remaining months according to the presented approach can be found in figure 8. And figure 9 shows the energy trade planning of each unit in the remaining months according to the average decomposition method. The energy planning of thermal units in the whole year is 10069189MWh, which is lower than the result using the average decomposition method by 187676MWh. According to the presented approach, the energy planning of wind power is 1878065MWh, which is more than the result using the average decomposition method by 40000MWh. The comprehensive cost of generation based on time sequential simulation is 242593939$, which is less than the result using average decomposition method by 4608098$.

![Figure 6. Monthly energy plan of each unit in July.](image1)

![Figure 7. Energy trade schedule of each unit in July.](image2)

The energy planning of multiple energy resources is coordinated by using the presented model and the time sequential simulation method. The clear energy power could be scheduled in priority so that the total generation costs could be reduced.

![Figure 8. Energy trade planning of each unit in the remaining months according to the presented approach.](image3)

![Figure 9. Energy trade planning of each unit in the remaining months according to the average decomposition method.](image4)
5. Conclusions
In the process of making monthly energy trade plan, average decomposition method gives priority to the demand of thermal and hydro units’ contract energy. When using this method, the energy is roughly distributed according to the capacity of the units, but the advantages and disadvantages of the units are not considered. Considering that time sequential simulation method could consider multiple resources and the technique of computer hardware and software has been improved, the time sequential simulation method can be taken as a viable option to deal with the problem of monthly energy trade planning. A monthly energy trade planning model for power systems with multiple power resources is proposed in this paper, and the time sequential simulation method is used to solve the problem.

Time sequential simulation method used in this paper constructs a trading plan simulation mode to meet the energy saving generation dispatch requirement. At the same time, the output characteristics, load characteristics and peak regulation characteristics of various energy resources are considered simultaneously. The mode can be solved by Cplex simulator. The simulation result can express the generation operation and daily generation plan of various energy resources.

Time sequential simulation method and the average decomposition method are compared in the case study. When using the time sequential simulation method, the wind power accommodation can be improved. The comprehensive generation costs in the studied month can be reduced on the premise of power system operation security by using the time sequential simulation method. And the energy saving effect and emission reduction effect are both obvious using the method presented in this paper. Moreover, by using the time sequential simulation method in monthly energy trade planning, the difficulty of daily dispatching is reduced to some extent in the actual operation of power grid.

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