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Joint Peak Shaving Energy Consumption Optimization Model and Simulation Analysis of Pumped Storage Power Unit and Coal-fired Power Units

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The regional power grid is mainly a thermal power system, so it is hard to meet increasing the need of difference between peak and valley loads and the demand of peak-load regulation. Units peaking mode directly related to the peaking economy, which becomes a serious problem. In this paper, from the perspective of optimization. Comprehensive consideration of pumped storage power units capacity and the factors influencing the load time, the optimization of load distribution for pumped storage power units and coal-fired power units, peak shaving modes was analyzed and the corresponding economic model was constructed. The application indicates that the best method of pumped storage power units and coal-fired power units. Pumped storage power units with 300 MW coal-fired power units with two-shift is the most obvious way to coal saving benefit. It provides a reference for energy-saving dispatching.

1. Introduction

As the country's primary energy supply, coals occupy around 70% of the whole energy consumption in China. The revolution of energy production and consumption provides solution for prominent contradictions between energy and environment(Yang et al., 2013). It is supposed to step up efforts to promote clean and efficient utilization of coal resources so as to realize maximal utilization. In particular, the installation capacity of 300MW coal-fired units and 600MW coal-fired units accounts for about 94% of the total installation capacity for thermal power-based power grids in northern areas. Along with accelerated growth of electrical demand, the difference increases between peak load and valley load. Currently, according to numerous documents(Abila, 2010), it is feasible to regulate peak load of power grids by means of two shifting between 320MW coal-fired units and 200MW coal-fired units(Li, 2012). In addition, the successful implementation of two shifting between 125MW coal-fired units and 200MW coal-fired units demonstrates that it is theoretically practical for 300MW coal-fired units and 600MW coal-fired units to undergo two shifting(Qi, 2013,Yang and Zhang,1989).As power shaving power sources, the pumped storage power stations have two characteristics(Zhang, 2007): 1. peak clipping and valley filling. Off-peak electric power of thermal power plants is used to run the pumps so as to increase the off-peak load rate and avoid high-energy consumption as well; during periods of high load demand, the stored water is released to produce electric power, helping increase electrical supply capacity at the peak state and also reduce fuel demand, maintenance costs, and pollutant emission. 2. Rapid start, flexible operation, high reliability, quick reaction to dramatic load change, self-starting ability, and access to such demands as frequency regulation, phase regulation, emergency standby, and black start(Wan, 1997).

Despite of different characteristics and emphasis of the numerous documents that the author referred to, all of them fail to conduct research on thermal power units, especially on the energy consumption from unified peak load regulation between pumped storage and over 300MW thermal power units. Therefore, given the large-scale modern units and the mounting difference between peak load and valley load of power grids, the economical analysis of peak load regulation schemes of large units exerts great significance on comparison and optimization of such schemes.

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2. Energy consumption analysis of typical peak load regulation schemes

Currently, the main peak load regulation schemes for coal-fired units in China contain: 1) low load operation. The units shall operate at the lowest possible load so as to increase electricity supply available. For this scheme, peak load regulation of thermal power units can be done regardless of energy consumption and pollutant emission amounts. In this regard, the units with small installation capacity and high energy consumption may possibly operate during periods of low load for a long time, while the units with large installation capacity and low energy consumption may suffer low utilization rate. Such conditions, if happened, will lead to low utilization rate of primary energy and even serious environmental pollution. 2) Two shifting, or start-stop peak load regulation. For this scheme, units operate according to the daily load curve. After the nighttime peak load time, the units will be shut down to the state of hot spare, waiting for a startup for the following daytime peak load the next day. Compared to scheme 1, in spite of the requirement of a frequent start-stop operation with heavy workload, this scheme is characterized by the large amount of available electricity supply and the ability to reach 100% load capacity, thus posing a more prominent effect to peak load regulation of power grids. As the coal-fired units witness upgraded operation and automation levels with improved and reasonable support services of main units and auxiliary units, the more and more obvious energy-saving superiority of two shifting operation renders this scheme to be safe, practical and reliable. It has become the fundamental measure with regard to peak load regulation of power grids.

2.1 Energy consumption for low load operation

Under low load operation, any deviation from rated working conditions would dictate the increase of energy consumption for thermal power units. If the difference of coal consumption when the load changes is neglected, B_L, the coal consumption at low load, can be estimated according to the following equation:

$$B_L = \sum_{i=1}^{\Omega} Z_i \cdot N_i \cdot b_0^i \cdot \tau_L^i \times 10^{-3} \tag{1}$$

2.2 Energy consumption for two shifting operation

There is frequent start-stop operation for the two shifting scheme. The start-stop loss decides whether the two shifting scheme is economical or not, and can be calculated through either experimentally or theoretically. With certain constraints, the experimental calculation always fail to represent real loss. The method of linear factors is usually used for theoretical calculation. Its basic thought is: the start-stop loss (H) during the whole start-stop process is divided into k phases, with m influential factors corresponding to each of the k phases. The loss amounts are calculated according to the characteristics and the influential factors of each phase. The corresponding expression is:

$$H = \sum_{i=1}^{k} \sum_{j=1}^{m} K_i^j t_i^j \tag{2}$$

A whole start-stop process is usually partitioned into several phases, namely load off, shutdown, unit shutdown, boiler ignition preparation, boiler ignition, boost, turn on, grid connection, load up, and thermal stability.

3. The optimized models of unified peak load regulation between pumped storage and thermal power units

Intended for the currently thermal power-based power grids, and in combination with characteristics of unified peak load regulation between pumped storage and thermal power units, the optimized models aim at minimizing the total coal consumption during the periods of peak load regulation and further reducing the pollutant emission amounts from electricity generation.

3.1 The model of peak load working conditions

During peak hours (from T_1 to T_2), the two-shift thermal power units start up and generate electricity under the peak-shaving state. At the same time, the pumped storage units help produce electric power, thus reducing the workload of corresponding m thermal power units. Then, the total coal consumption (F_p) of the two shifting units during peak hours is expressed as:

$$F_P = \int_{T_1}^{T_2} \sum_{i=1}^{m} \left[\mu_{p,\ i}^{t} B_i \left(P_{p,\ i}^{t} - N_{v,\ i} \right) + \mu_{P,\ i}^{t} \left(1 - \mu_{p,\ i}^{t-1} \right) \left(H_i + W_i \times t \right) \right] dt \tag{3}$$

3.2 The model of valley load working conditions

During valley hours (from T_3 to T_4), off-peak electric power of thermal power plants is used to run the pumps, thus increasing the workload of these units. Assuming that water is pumped from T3 to T4, and there is a total of n thermal power units running the pumps, the total coal consumption (F_v) of the two shifting units during valley hours is expressed as:

$$F_V = \int_{T_3}^{T_4} \sum_{i=1}^{n} \left[\mu_{v,\ i}^{t} B_i \left(P_{v,\ i}^{t} + \frac{N_{v,\ i}}{\eta_p} \right) + \mu_{v,\ i}^{t} \left(1 - \mu_{v,\ i}^{t-1}\right)\left(H_i + W_i \times t\right) \right] dt \tag{4}$$

2.3 Objective functions and constraints

According to the above analysis, it can be obtained that within a daily peak load regulation period, the total coal consumption (F) is equal to the sum of F_p and F_v. Considering that the unified peak load regulation aims at minimizing the total coal consumption during the whole periods of peak load regulation, the objective is then optimized as:

$$\min F = F_P + F_V \tag{5}$$

Corresponding constraints are:

$$\sum_{i \in \Omega_G} P_i = P_P \tag{6}$$

$$\sum_{i \in \Omega_G} P_i = P_V \tag{7}$$

$$\mu_{p,\ i}^{t} P_{i,\ min} \le P_{p,\ i}^{t} \le \mu_{p,\ i}^{t} P_{i,\ max} \tag{8}$$

$$\mu_{v,\ i}^{t} P_{i,\ min} \le P_{v,\ i}^{t} \le \mu_{v,\ i}^{t} P_{i,\ max} \tag{9}$$

$$\Delta P_i^{-} \le P_i^{t} - P_i^{t-1} \le \Delta P_i^{+} \tag{10}$$

4. Examples and analysis

4.1 Introduction to the examples

The power grid of the researched area in the paper mainly uses thermal power units. A randomized typical day in 2009 was chosen, whose peak load was 135,171MW and valley load 78,617 MW. The difference between peak load and valley load accounted for about 41.8% of the peak load. Table 1 shows the start-stop loss of 300MW units and 600MW units involved in peak load regulation. Table 2 shows the fundamental parameters of the thermal power units in the researched area. Assuming that the capacity of pumped storage units involved in peak load regulation was 2,530 MW.

To balance the difference between peak load and valley load, and considering that the required electric quantity for pumped storage units at low load is distributed equally to every peak load regulation units in the power grid, it is essential to maintain the thermal power units at a 56.5 percentage of rated load. Alternative schemes of the unified peak load regulation are as follows:

Table 1: The start-stop loss of 300MW units and 600MW units

item		Start-stop phase				
		unit shutdown	boiler ignition preparation	boiler ignition, boost, turn on, and grid connection	load up	thermal stability
Time/ h	300MW	——	0.50	0.83	0.82	1.00
	600MW	——	0.50	0.67	0.75	1.00
300MW units		1.15	7.69	23.75	1.82	2.34
600MW units (WC)		2.29	14.01	64.69	6.55	4.68
600MW units (AC)		2.30	14.32	64.98	7.94	4.68

Table 2: Fundamental parameters of the thermal power units in the researched area

Type of units	Number of units	Percentage /%	a_i /10^{-2}	b_i /10^{-2}	c_i	$P_{i,min}$ /MW	$P_{i,max}$ /MW	$\triangle P_i^-$ /MW·min^{-1}	$\triangle P_i^+$ /MW·min^{-1}
1000MW	6	4.4	0.0049	-10.18	335.00	500	1000	-20	20
600MW (WC)	77	33.6	0.01	-20.88	379.26	0	600	-12	12
600MW (AC)	31	13.6	0.03	-35.67	434.85	0	600	-12	12
300MW	219	48.1	-0.03	-4.46	363.49	0	300	-6	6

scheme	Type of units	percentage /%	Unit for load distribution				scheme	Type of units	percentage /%	Unit for load distribution			
			300 MW	600 MW (WC)	600 WM (AC)	1000 MW				300 MW	600 MW (WC)	600 WM (AC)	1000 MW
1	300MW	30	1	1	1	1	13	600MW	30	1	1	1	1
2			1	—	—	—	14			—	1	1	—
3			—	1	1	1	15			1	—	—	1
4			—	2	2	1	16			2	—	—	1
5		50	1	1	1	1	17		50	1	1	1	1
6			1	2	2	1	18			3	1	1	2
7			—	1	1	1	19			1	—	—	1
8			—	2	2	1	20			2	—	—	1
9		70	1	1	1	1	21		70	1	1	1	1
10			1	2	2	1	22			3	1	1	2
11			—	2	2	1	23			1	—	—	1
12		92	1	1	1	1	24			2	—	—	1
							25		89	1	1	1	1

Note: "—"denoted that the units maintain the original operational states. The numbers of 1, 2 and 3 denoted the priority with regard to load distribution.

4.2 Calculation results and analysis

According to the schemes in Table 3, the GAMS software was used for solutions of the established models in the paper. Compared to the low load regulation scheme, coal conservation and emission reduction of the unified peak load regulation scheme were shown in Figure 1 and Figure 2 as follows:

In a load regulation period (usually for 8h), if the 300MW coal-fired units operated under the two-shift state, the 3rd, 6th, 8th, 9th, 10th, 11th and 12th schemes possessed higher economy in comparison with the low load regulation scheme. The 11th and 12th schemes had the shortest critical time of about 2h.

(1) In a load regulation period (usually for 8h), if the 600MW coal-fired units operated under the two-shift state, the 24th scheme possessed higher economy in comparison with the low load regulation scheme, with the critical time of about 4h.

(2) With the increasing capacity of pumped storage units that were involved in peak load regulation, the annual coal-saving amount saw a rising trend for the unified peak load regulation scheme within the same peak load regulation period. The reason was that the mounting capacity of pumped storage units helped reduced the start-stop times of thermal power units on the one hand and increased correspondingly the load rate of thermal power units on the other hand.

It can be seen from Figure 3 and Figure 4:

(1) As the proportion of pumped storage units rose, the energy consumption for the unified peak load regulation scheme was reduced, and the critical time for the 24th scheme was shortened from 5h to 4h as well. The reason was that the increasing capacity of pumped storage units not only increased the load rate of thermal power units, but reduced the start-stop times of thermal power units.

The coal consumption for peak load regulation was the lowest for the two-shift 12th scheme in which the full capacity of pumped storage units was put into use. Compared to the low load regulation scheme, an annual 4.06 - 10.48 million ton of standard coal was saved, corresponding to an emission reduction of 9.00 - 23.26 million ton CO_2, 1.15 - 2.96 million ton NOx, and 977 - 2,523 ton SO_2. In this way, the researched area could harbor an effective reduction of the total amount of pollutant emission and also an annual revenue of

￥2,841.80 - 7,335.99 million (if the coal price was ￥700/t and the annual operation time was 5000h).

The above calculation results and analysis show that it is economically feasible to implement unified peak load regulation between pumped storage units and the two shifting of 300 MW thermal power units and 600 MW thermal power units. To transform the low load operation scheme into the two shifting operation scheme for a certain scale of 300 MW thermal power units and 600 MW thermal power units can better relieve pressure of peak load regulation in the researched area, and can also reduce the originally great daily and weekly difference between peak load and valley load in a more effective manner. This transformation can help improve the economy of peak load regulation as well.

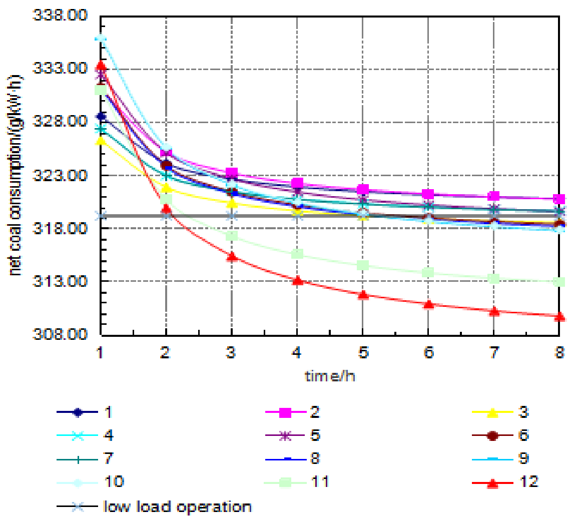

Figure 1: Peak coal consumption curve of 300MW

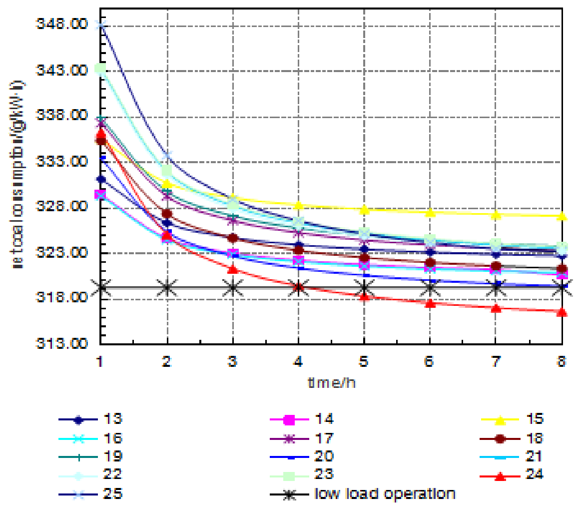

Figure 2: Peak coal consumption curve of 600MW

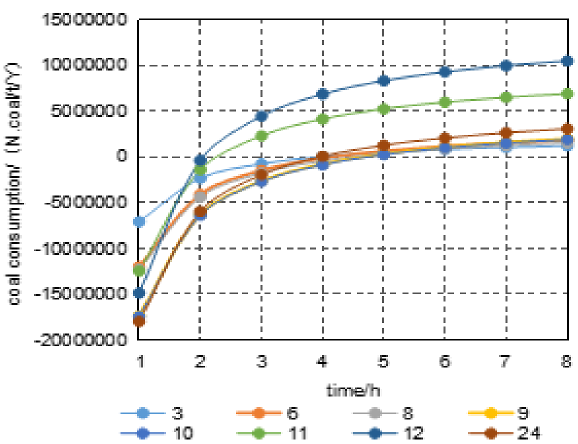

Figure 3: Comparison of coal conservation and emission reduction for different peak load regulation schemes (for 70% capacity of pumped storage units)

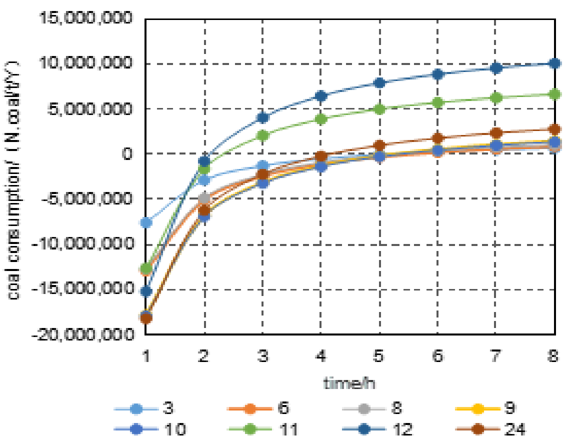

Figure 4: Comparison of coal conservation and emission reduction for different peak load regulation schemes (for 100% capacity of pumped storage units)

5. Conclusion and proposal

(1) By establishing the optimized models of unified peak load regulation between pumped storage units and thermal power units, the paper finds that energy consumption is the lowest for the 12th scheme. On the premise that the capacity and peak load regulation capability of power grids remain unchanged, and in comparison with the low load regulation scheme, the annual coal-saving amount increases as the capacity of pumped storage units for peak load regulation increases. Thus the total amount of pollutant emission in the researched area can be reduced effectively. Meanwhile, the 12th scheme will be more advantageous if the capacity benefit and social

benefit brought by the scheme are counted in.
(2) Through data analysis of two kinds of capacity inputs for pumped storage units, it can be obtained that it is the most economical way to put the 100% pumped storage units into peak load regulation. However, when determining the exact percentage of capacity, it is supposed to consider such factors comprehensively as the potential spinning reserve capacity and emergency capacity for pumped storage units.

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