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Peaking Shaving Energy Model for Combined Optimization of Pumped Storage Power Plant and Coal-fired Power Unit Considering the Farmland Drainage and Irrigation

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Abstract: Irrigation station is the large energy consumed unit of water conservancy drainage and irrigation in north China. A region in that part of China dominated by thermal power is difficult to meet the requirements of the increasing differences between peak and valley as well as economy of peak shaving, a concern of which is expected to be solved at present. Through describing the status quo of farmland drainage and irrigation and starting from the optimized perspective, the thesis presents a peak shaving energy optimized model for combining pumped storage power and coal-fired power unit considering farmland drainage and irrigation. GAMS software is used to obtain solution of the model as well. Example shows that farmland drainage and irrigation cost reduces 412,300 yuan per hour, SO_2, NOx and CO_2 emissions decrease 7.49 tons, 30.14 tons, and 51,935.45 tons respectively, and total cost of peak shaving lowers 10.8577 million yuan in a daily peak period. The model serves as a way to improve economy and environmental benefits of regional power grid peak shaving, and provides a reference for farmland drainage and irrigation and regional energy saving schedule.

Keywords: *farmland drainage and irrigation, coal-fired power unit, pumped storage power plant, two-shift, peaking load regulation, economy*

1. Introduction

With the robust growth of China's agriculture, energy consumption of farm machinery has become a striking concern in agricultural production. According to the improved United Nations' standards for farmland drainage and irrigation, electric irrigation station in rural areas has been an indispensable water conservancy infrastructure [1-2]. In the region where the water is in the low position while the farmland is in the higher place in particular, it must make good use of irrigation station to irrigate farmland. In addition, it plays a role in storing water, so as to solve severe farmland water shortage in dry seasons. Therefore, the irrigation pumping station capacity and irrigation interest in north China in particular have increased by hundreds of times. At present, the area enjoys more than 500,000 fixed irrigation stations of large, middle and small sizes, with the total installed capacity of more than 7,000 KW and drainage area of nearly 500 million acres. The application of irrigation station as well as irrigation and drainage channels is the current trend of drainage and irrigation of water conservancy project, but with the continuously expanding irrigated area, energy consumption of irrigation station is rising accordingly [3-4].

Meanwhile, north China is mainly based on thermal power grid, among which, the installed capacity of the coal-fired power unit with 300MW and 600MW accounts for 94% of the total grid installed capacity. While electricity demand is accelerating, difference between peak and valley load is expanding as well [5]. On the base of the actual situation of grid power supply in the region, it is accessible to enhance grid peaking load regulation by making full use of the peaking shaving capacity of existing grid electricity, and conducting qualified technical and economic analysis for expanding peaking shaving capacity. As the power source of peaking shaving, pumped storage power plant shares two major characteristics. The first one is to regulate the peak value and fill the valley. Pumped storage power plant performs load pumping in low grid and improves low load rate of thermal power plant, preventing thermal power unit from working with low load but high energy consumption. When load demand increases, the pumped storage power plant works by generating power, which can enhance the power supply capacity of the system in peak period [6], and at the same time, lower costs of unit fuel and repair maintenance, and reduce pollutant emissions, thus bringing huge benefits to consumption reduction of power plant and to social environment. The other feature is rapid start, flexible operation and high reliability. The model can rapidly respond to drastic changes of load, and undertake FM, PM, emergency reserve and black start with its self-starting capability [7]. At present, many documents have already proved that two-shift of 320MW and 200MW coal-fired units is accessible to grid peaking shaving [8]. According to the functioning experience of two-shift of 125MW and 200MW coal-fired units, it shows the two-shift peak shaving of 300MW and 600MW coal-fired units [9-11] is feasible in technical theory. However, there is not the research that combines pumped storage power and coal-fired power unit considering farmland drainage and irrigation.

Therefore, in view of relatively extensive farmland drainage and irrigation, large-scale generators and increasingly expanding peak-valley differences, it is significant to analyze and optimize the combined peak shaving of farmland drainage and irrigation and the large units.

2. Energy consumption analysis of a typical peak shaving scheme:

According to the practical operation of the coal-fired units in China, the main choices of coal-fired unit's peak shaving are: 1) low load operation. To increase the adjustable output unit, unit should be operated in allowed minimum load as much as possible. At present, some domestic power plants have made and implemented relevant measures such as blending or plasma cooperation to guarantee the unit to run at 50% rated load for oil stable-combustion, for the purpose of achieving the depth of the peak load [12]. In low load scheme, regardless of energy consumption and pollutant emission levels, load of thermal power unit is able to regulate its peak. Balanced load mode makes the small but high energy-consuming unit operate for a long time under low load, yet the equipment of large installed capacity and with high efficiency is low at utilization rate, leading to a low energy utilization rate and serious environmental pollution. 2) Two-shift running mode refers to the start-stop operation scheme. In this scheme, the unit, according to the power load curve during the day, stops running after the evening rush and keeps hot standby. Then the unit starts next morning to meet power requirement in the morning [13]. Compared with low load operation, in spite of its frequent starts and stops of the main and auxiliary engines, the high workload and a complex operation, two-shift running mode features itself with a 100% load of operation, which is important in power grid peak shaving. The two-shift advantages have become increasingly obvious thanks to the improved support services of the main and auxiliary machinery of coal-fired power plants, and the increased unit operation level and automation degree. Thereby, this scheme has become a safe and reliable solution to the actual load of peak, serving as a fundamental measure to solve power grid peak shaving [14].

2.1 Coal consumption of peak shaving in low load

Low load operation, if deviating from the rated conditions, will lead to the increase of unit energy consumption. If ignoring the load change of the unit coal consumption, the coal consumption quantity in low load mode BL can be estimated in the following formula:

$$B_L = \sum_{\mathrm{i}=1}^{\Omega} Z_{\mathrm{i}} \cdot N_{\mathrm{i}} \cdot \mathrm{b}_0^{\mathrm{i}} \cdot \tau_L^{\mathrm{i}} \times 10^{-3} \tag{1}$$

2.2 Coal consumption of two-shift peak shaving

Frequent starts and stops are distinguishing features of two-shift scheme, so the loss of starts and stops is the decisive element in its economical possibility. At present, there are two methods to calculate the cost of starts and stops: testing and theoretical calculation. The former, due to its limitation, can hardly characterize the true level of the unit start-stop loss. And the latter one, commonly used as linear factor method, has its own content as following: the start-stop loss of the entire start-stop process H is divided into k phases, and m factors of every stage. The loss can be calculated according to the characteristics of each stage and its influence factor. Its formula is presented as

$$H = \sum_{\mathrm{i}=1}^{\mathrm{k}} \sum_{\mathrm{j}=1}^{\mathrm{m}} K_{\mathrm{i}}^{\mathrm{j}} \mathrm{t}_{\mathrm{i}}^{\mathrm{j}} \tag{2}$$

A complete start-stop process is usually divided into the following parts: reducing load, downtime, machine stopping, preparation for the boiler ignition, igniting, boosting, impulse starting, grid connection, lift load and thermal stage of equipment. The loss of each stage can be calculated as recorded in the references [14].

2.3 Farmland drainage and irrigation power in peak shaving

Farmland drainage and irrigation is a kind of side response to the demand of peak shaving mode, which is a more flexible load plan [15-16]. Agricultural drainage and irrigation can be regarded as a sort of virtual backup power to improve load rate and utilization rate of equipment and solve the concern of insufficient regional system load capacity. At the same time, it also can reduce the operating costs and increase productivity of power enterprises. The plan of involving the agricultural drainage and irrigation in peak-load shaving has the following marked characteristics: 1) Fast response. Under the circumstance of a serious shortage of adjustable capacity and the absence of peak-load regulation power source, the interruption of energy in farmland irrigation and drainage can be a quick back-up resource; 2) High economic efficiency. Peak-load shaving can be achieved by involving agricultural drainage and irrigation, so as to alleviate the pressure of the investment of power plant expansion and load power supply; 3) It can reflect different varieties of farmland drainage and irrigation and farmers' willingness to use electricity. Different fields need different types of users and power characteristics of irrigation and drainage. Farmland drainage and irrigation can, depending on all kinds of intention of farmers, change the mode of electricity consumption, and thus make a scientific decision-making to allocate power resource [17]. Therefore, the joint mode of farmland drainage and irrigation in pumped storage and thermal power unit represents the best choice of demand-supply peaking load regulation system.

3 Peaking shaving energy model for combined optimization of pumped storage power plant and coal-fired power unit considering the farmland drainage and irrigation

3.1 Thoughts of the model

The peak shaving approach that combines pumped storage power and coal-fired power unit in consideration of farmland drainage and irrigation is based on the current power grid led by coal-fired power units [18-19]. The model also comprehensively integrates the features of two-shift peak shaving of farmland drainage and irrigation, pumped storage power plant and coal-fired power unit. Aims at minimizing total coal consumption when power system is at peak period [20-22], this method can reduce peak shaving energy consumption of power system, cut down pollutant emissions from power generation and improve agricultural irrigation quality.

3.2 Objective function

In terms of regional power grid, its total operation cost includes the coal consumption cost on generating power of thermal power units and the one on emitting major pollutants. The objective function is to meet the load requirements of regional grid, and at the meanwhile, to purse the lowest cost on regional grid operation, which can be illustrated by the following formula [23-29]:

$$\min \mathrm{Y} = F_0 \cdot F + Q + E_0 \cdot E \tag{3}$$

Among it,

$$\begin{cases}
F = \sum_{t=1}^{T}\sum_{i=1}^{I}\left[\mu_i^t \mathrm{B}_i\left(P_i^t + f\left(N_{P,k}^t\right) + g\left(M_{P,l}^t\right)\right) + \mu_i^t\left(1-\mu_i^{t-1}\right)S_i(t)\right] \\
Q = \sum_{t=1}^{T} Q_t = \sum_{t=1}^{T}\sum_{i=1}^{I}\begin{bmatrix} 3.2\times 10^{-6}\left(P_i^t + f\left(N_{P,k}^t\right) + g\left(M_{P,l}^t\right)\right)^2 \\ -0.53\left(P_i^t + f\left(N_{P,k}^t\right) + g\left(M_{P,l}^t\right)\right) + 335 \end{bmatrix} \\
f\left(N_{P,k}^t\right) = \begin{cases} -N_{P,k}^t & t \in [T_1, T_2] \\ \dfrac{N_{P,k}^t}{\eta_P} & t \in [T_3, T_4] \end{cases} \\
g\left(M_{P,l}^t\right) = \begin{cases} -M_{P,l}^t & t \in [T_1, T_2] \\ M_{P,l}^t & t \in [T_3, T_4] \end{cases} \\
S_i(t) = H_i + W_i \times t \\
E_0 = 0.6 \times \lambda_1 \times \lambda_c \\
E = \sum_{t=1}^{T}\sum_{i=1}^{m}\mu_i^t\left(\dfrac{G_{SO_2,i}}{N_{SO_2}} + \dfrac{G_{NO_x,i}}{N_{NO_x}} + \dfrac{G_{CO_2,i}}{N_{CO_2}}\right) \\
G_{SO_2,i} = \dfrac{32}{16} \times b_i \times S_{ar} \times t \times \left(1-\eta_S\right) \\
G_{NO_x,i} = \dfrac{30.8}{14} \times b_i \times N \times \dfrac{\eta_n}{m} \times \left(1-\eta_X\left(\beta_i\right)\right) \\
G_{CO_2,i} = \mu \times b_i \\
\eta_X\left(\beta_i\right) = \begin{cases} 0 & 0 \le \beta_i < 55\% \\ 0.85 & 55\% \le \beta_i \le 100\% \end{cases}
\end{cases}$$

In accordance with Standards and Calculation Methods for Sewage Charges (Trial Implementation) issued in 2003 by the Chinese government, equivalent value of the pollutant emission in thermal power plant is showed as the table1.

***Table 1.** Equivalent value of the pollutant emission in thermal power plant [30-32]*

Pollutants	Sulfur dioxide	Nitrogen oxide	Carbon dioxide
pollution equivalent value	0.95	0.95	16.70

3.3 Constraints

1) Power balance constraint

$$\sum_{i=1}^{I} P_i^t + \sum_{\mathrm{k}=1}^{K} N_{P,\mathrm{k}}^t + \sum_{\mathrm{l}=1}^{L} M_{P,\mathrm{l}}^t = P^t \tag{4}$$

2) System reserve capacity constraint

$$\sum_{i=1}^{K} \mathrm{r}_{i,\ t} \ge R_t \tag{5}$$

3) Upper and lower limit of generating unit

$$P_{\mathrm{i},\ min} \le P_i \le P_{\mathrm{i},\ max} \tag{6}$$

4) Constraints of minimum operation and outage time

$$\mu_i^t = \begin{cases} 1, & 1 \le \mathrm{x_i}(t) \le T_{\mathrm{i}}^{\mathrm{on}} \\ 0 & -T_{\mathrm{i}}^{\mathrm{off}} \le \mathrm{x_i}(t) \le -1 \end{cases} \tag{7}$$

5) Lift rate constraint

$$\Delta P_i^- \le P_i^t - P_i^{t-1} \le \Delta P_i^+ \tag{8}$$

3.4 Solution

Since the research problem in this thesis is nonlinear and non-convex with the mixed integer programming of discrete constraints, the author of the thesis proposes to apply GAMS software to optimize and solve the problem.

4 Simulation calculations:

4.1 Simulation example

The example of the thesis is based on the farmland and power grid of an area in north China, in the region of which, the farmland area is 6.2154 million mu (1mu=0.0666666666667acre), and the effective irrigation area covers 5.7021 million mu, accounting for 91.74% of cultivated land area. The area enjoys 3,231 farmland drainage and irrigation pumping stations, and a total of 4,209 sets of 2,163.87MW. The power grid in the area is dominated by thermal power, among which, the installed capacity of the coal-fired power unit of 200MW - 600 MW occupies about 94% of the total installed capacity of the power grid. Table2 shows the basic parameters of he main thermal power units in the area. Table3 presents the start-stop loss situation of 200MW, 300MW and 600MW coal-fired power units involving in peak shaving. The author sets the total capacity of peak shaving pumped storage units as 1,500MW.

***Table2.** Coefficients of coal-fired power units*

Unit type	Unit number	Proportion /%	a_i /10^{-5}	b_i /10^{-3}	c_i	$P_{i,min}$ /MW	$P_{i,max}$ /MW	ΔP_i /(MW·min^{-1})
1000MW	2	4.78	50.00	-101.80	335.00	500	1,000	20
600MW (humid cold)	12	17.22	108.00	-206.76	395.21	0	600	12
600MW (air cold)	16	22.96	72.00	-174.9	420.21	0	600	12
300MW	51	36.59	54.00	-141.03	418.22	0	300	6
200MW	28	13.39	42.03	-123.91	431.42	0	200	6

***Table 3.** Start-stop loss factor of coal-fired power units* (t standard coal/h)

Program		Start-stop stage				
		unit stop	boiler ignition preparation	igniting, boosting, impulse starting,grid connection	lift load	thermal stability of equipment
process time/h	200MW	——	0.50	0.8	0.50	0.60
	300MW	——	0.50	0.83	0.82	1.00
	600MW	——	0.50	0.67	0.75	1.00
200MW unit		0.77	6.45	20.15	1.42	1.56
300MW unit		1.15	7.69	23.75	1.82	2.34
600MW humid cold unit		2.29	14.01	64.69	6.55	4.68
600MW air cold unit		2.30	14.32	64.98	7.94	4.68

The calculating analysis makes uses of the representative day of the regional grid, in June, 2014, showed as figure1. Taken 24h as a decision-making cycle, the calculation tests and analyzes the applicability of the objective function of the algorithm in the thesis and covers the interests generated by optimization.

4.2 Simulation results analysis

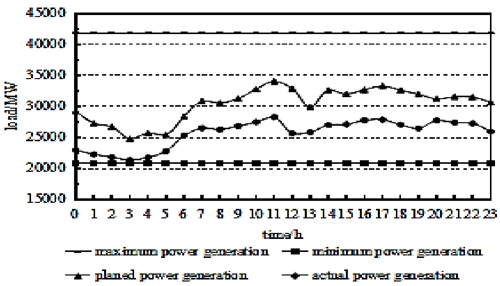

Figure 1 Typical daily average load curve

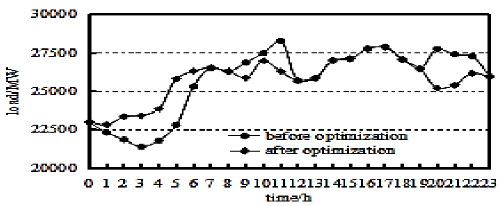

Figure 2: Comparison of loads of the system before

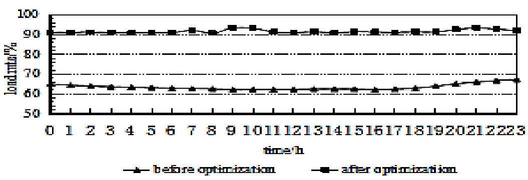

Figure 3: Comparison of units rate of the system before and after optimization

According to figure1, the present peak shaving approach of power grid is dominated by low load peak shaving, thus the coal-fired unit of the grid should be maintained in the vicinity of 65% rated load to realize peak shaving. At present, the required power volume of the current farmland drainage and irrigation and pumped storage power plant equally shares to every grid peak shaving unit. To remain the grid peak shaving unchanged and consider low load, the current method is altered to two-shift peak shaving of and pumped storage power and coal-fired power unit considering farmland drainage and irrigation. The proposed model is optimized to obtain solution by means of GAMS software; thereby it is accessible to load conditions in different periods before and after the optimization of regional grid. As figure2 shows, the system load becomes more moderate after the application of the optimized model: (1) the peak load is reduced from 26,510MW to 28,310MW; (2) the power quantity difference in every period after optimization is decreased, achieving striking effect of peak shaving and valley filling.

From the analysis of load rate of regional power grid unit (see figure3), the average daily load rate of the optimized regional fire-coal unit rises from about 65% before optimization to above 90% after optimization, and the average load rate is significantly improved after optimization.

By researching the discharging quantity of pollutants and total generating cost analysis before and after optimization (see table4), it is showed that the model reduces farmland drainage and irrigation costs and total grid peak shaving cost in the region, with drainage and irrigation lowering 412, 3000 Yuan per hour, the emission of SO2, NOx and CO2 respectively

7.49 tons, 30.14 tons and 51,935.45 tons and the peak shaving total cost 10.8577 million Yuan in a daily peak period.

Table 4: *The discharging quantity of pollutants and total peak shaving cost before and after optimization*

	SO_2	NO_x	CO_2	drainage and irrigation energy consumption1)	total peak shaving cost2)
unit	t/d	t/d	t/d	million Yuan/h	million Yuan/d
before optimization	74.55	72.91	516,889.87	1.0603	157.5979
after optimization	67.06	42.77	464,954.42	0.648	146.7402

Notes: 1) Peak power price is calculated with 0.49 Yuan/kW•h, and valley power price 0.30yuan/kW•h; 2) Standard coal is calculated with 600yuan/t.

The above calculation analysis indicates that the two-shift peak shaving of pumped storage power and coal-fired power unit considering farmland drainage and irrigation is not only beneficial to ease the pressure of regional grid peak shaving and improve economy of system peak shaving, but also cut down the discharging quantity of major pollutants and total peak shaving cost in the region.

5 Conclusions

To explore energy consumption of the combined peak shaving of pumped storage power and coal-fired power unit considering farmland drainage and irrigation, the thesis constructs an optimized peaking shaving model for combining pumped storage power and coal-fired power unit considering the farmland drainage and irrigation and carries out analysis of simulation example.

(1) The proposed model is able to optimize water conservancy projects and effectively mitigate high energy consumption in irrigating areas.

(2) The peak shaving model in the thesis can lift load rate of thermal power unit and decrease power generating coal consumption of coal-fired power unit by means of two-shift peak shaving of combining pumped storage power and coal-fired power unit together in consideration of farmland drainage and irrigation, thereby economy and environmental benefits of the regional power grid peak shaving are facilitated.

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