Optimal Electric Energy Production scheduling for Thermal-Hydro Electric Power Systems

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***Abstract*—A method for optimal electric energy production of thermal-hydro power systems is presented in this paper. The electric energy produced by hydroelectric plants and coal-fired plants is divided into 4 components: potential energy, kinetic energy, water-deep pressure energy and reservoir energy. A new and important concept, reservoir energy, is proposed, based on which is divided into a number of water bodies, for example 3 water bodies, and a reservoir is analyzed in a new way. This paper presents a optimal scheduling solution of electric energy production of thermal-hydro power systems based on multi-factors analytic method, in which some important factors, such as load demand, reservoir in-flow, water-consumed volume increment rate of hydroelectric plants or converted from coal-fired plants, and so on are given to model the objective function and the constraints. A study example with three simulation cases is carried out to illustrate flexibility, adaptability, applicability of the proposed method.**

Keywords- Thermal-hydro power systems; optimal electric energy productio; component and factor analysis; reservoir energy; hydro-energy conversion

I. INTRODUCTION

Water is one of the important renewable energy source and coal is a non-renewable energy source. For optimal scheduling of thermal-hydro power systems, it is the first thing that water must have much more priority to be used for electric energy production than coal so as to supply the demand load. It is an important study task how to minimize the sum of water-consumed volume of the hydroelectric plant and water-consumed volume converted from the coal-consumed volume of coal-fired plants in thermal-hydro power system dispatch.

In modeling electric energy production of hydroelectric plants, some pioneer did many significative works. For the portfolio management of a scandinavian power supplier, a linear stochastic model with hydraulic power plants under uncertain inflow and market price conditions is introduced [1]. In [2], price uncertainty by scenarios and a model for maximizing risk-adjusted profit within an asset-liability framework is represented. A new multi-loop-cascaded governor, with which the performance specifications and stability margins are improved significantly even in the presence of some uncertainties, is proposed to use for hydro turbine control [3] and some other stochastic programming models are proposed to represent the energy systems [4]. However, with the achievements in recent liberalization of the electricity market, the discussion about improving the assumptions and considering further aspects of actual system operations is far from ending.

This paper presents a novel method for modeling hydro-energy conversion and an optimal component and factor analytic method for electric energy production of large-scale thermal-hydro power systems, taking some energy component, such as potential energy, kinetic energy, water-deep pressure energy and reservoir energy into consideration, and also taking some influence factors, such as load demand, reservoir in-flow, water-consumed volume increment rate, and so on, into account.

II. HYDRO-ENERGY CONVERSION

In a large-scale reservoir, if there is a hydro-mechanical-electric coupling system, with a shaft leading the reservoir water through penstock to a hydro turbine, the potential, kinetic and water-deep energy in water is harnessed by the HME coupling system and create electricity from it. For each HME system, the amount of electric energy transformed form hydro energy in reservoir depends on the forces applied on the water body in intake and tailrace of the pressure tunnel. In intake of the pressure tunnel, basing on the traditional analysis method, there is gravitational force corresponding to the potential energy, kinetic force corresponding to kinetic energy and pressure force corresponding to water-deep pressure energy. In this paper, besides three traditional forces there are another three reservoir forces applied to the water body in intake if a reservoir is divided into three water bodies when modeling the hydroelectric energy of large-scale reservoir. These three reservoir forces applies to the water bode in intake of a pressure tunnel and do work in respective part, which is called 'reservoir energy' in this paper, as shown in Figure 1.

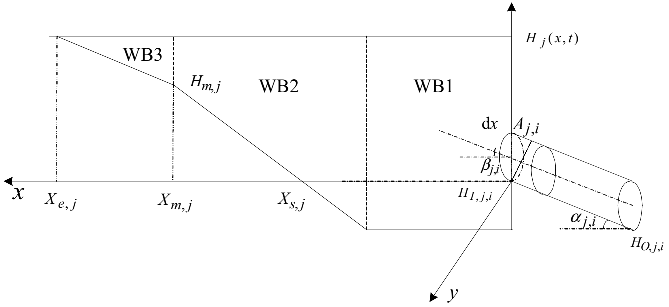

Figure 1. Divided water bodies of a large-scale reservoir

Because of difference in kinetic energy, potential energy, energy converted from water-deep pressure energy, the energy converted from self-weight, reservoir energy, there is a part of energy transformed into electric energy. For a unit i in plant j, the electric energy converted by a HME system in unit time(for example one second) may be expressed in a form of kilo-watt may be formulated in MWs:

$$E_{H,j,i}(H_j, Q_{G,j,i}) = f_1 + f_2 + f_3 + f_4 + f_5 + f_6 \tag{1}$$

where

$$f_1 = 9.81[(H_j(x,t) - H_{I,j,i}) - p_{O,j,i})]Q_{G,j,i} \tag{2}$$

$$f_2 = 9.81 * \frac{1}{2g}[v_{I,j,i}^2 - v_{O,j,i}^2]Q_{G,j,i} \tag{3}$$

$$f_3 = 9.81[H_{I,j,i} - H_{O,j,i}(t)]Q_{G,j,i} \tag{4}$$

$$f_4 = \frac{9.81 X_{s,j} Y_j [H_j(x,t) - H_{I,j,i}]}{Y_j [H_j(x,t) - H_{I,j,i}]} \cdot \sin\beta_{s,j}\cos(\alpha_{I,j,i} - \beta_{s,j})\cos^2\gamma_{s,j,i} \cdot Q_{G,j,i} \tag{5}$$

$$f_5 = \frac{9.81 Y_j (X_{m,j} - X_{s,j})(2H_j(x,t) - H_{m,j} - H_{I,j,i})}{2Y_j [H_j(x,t) - H_{I,j,i}]} \cdot \sin\beta_{m,j}\cos(\alpha_{I,j,i} - \beta_{m,j})\cos^2\gamma_{m,j,i} \cdot Q_{G,j,i} \tag{6}$$

$$f_6 = \frac{9.81 Y_j (X_{e,j} - X_{m,j})(H_j(x,t) - H_{m,j})}{3Y_j [H_j(x,t) - H_{I,j,i}]} \cdot \sin\beta_{e,j}\cos(\alpha_{I,j,i} - \beta_{e,j})\cos^2\gamma_{e,j,i} \cdot Q_{G,j,i} \tag{7}$$

where f_1 is energy converted from water-deep pressure energy, f_2 is energy converted from kinetic energy, f_3 is energy converted from potential energy, f_4 - f_6 is energy converted from reservoir energy. $Q_{G,j,i}$ is generation flow of generator i in plant j, $\alpha_{j,i}$ is the angle of the pressure tunnel for each generating unit, $H_j(x,t)$ is water-storage level elevation in reservoir j at time t, $H_{I,j,i}$ is a position elevation of the intake of the pressure tunnel relative to sea level, $\beta_{s,j}$, $\beta_{m,j}$ and $\beta_{e,j}$ is angle between x direction and the line passing through the gravity center of water body WB1, WB2, WB3 and axial origin respectively, $D_{j,i}$ and $A_{j,i}$ is diameter and sectional area of the pressure tunnel in the intake respectively, j denotes plant index, $X_{s,j}$, $X_{m,j}$ and $X_{e,j}$ is starting point of water body WB1, WB2 and WB3 in x direction, Y_j is width of the dam, $\gamma_{s,j,i}$, $\gamma_{m,j,i}$ and $\gamma_{e,j,i}$ is angle of the water body WB1, WB2 and WB3 between the center line of x direction and the pressure tunnel of unit i in reservoir j respectively, $T_{\max,j,i}$ is maximal utilization hours for the rated capacity of hydroelectric, $N_{R,j}$ is year number of a scheduling period.

The electric power $P_{H,j,i}$ of a generator is formulated:

$$P_{H,j,i} = \frac{E_{H,j,i}}{T} \tag{8}$$

where T is scheduling period of the hydroelectric plants. For a unit time(one second), $P_{H,j,i} = E_{H,j,i}$.

III. OPTIMAL SCHEDULING FOR ELECTRI ENERGY PRODUCTION

A. Water Consuption Volume

For a hydropower generator, the variation of electric energy is obtained by differentiating (1) with respect to $Q_{G,j,i}$:

$$\Delta E_{H,j,i} = [\partial f_1 + \partial f_2 + \partial f_3 + \partial f_4 + \partial f_5 + \partial f_6] \cdot \Delta Q_{G,j,i} = \frac{\partial f_1 + \partial f_2 + \partial f_3 + \partial f_4 + \partial f_5 + \partial f_6}{T} \cdot \Delta W_{H,j,i} \tag{9}$$

Water-consumed volume increment rate is defined to be a ratio of the variation of the water-consumed volume and the variation of electric power output of a hydropower generator:

$$\lambda_{H,j,i} = \frac{\Delta W_{H,j,i}}{\Delta E_{H,j,i}} = \frac{T}{\partial f_1 + \partial f_2 + \partial f_3 + \partial f_4 + \partial f_5 + \partial f_6} \tag{10}$$

B. Coal Consuption Volume

For a thermal power-driven generator, the coal-consumed volume is formulated as a quadratic function of electric power, as shown in the following form:

$$F_{T,k,l} = a_{T,k,l}E_{T,k,l}^2 + b_{T,k,l}E_{T,k,l} + c_{T,k,l} \tag{11}$$

where $F_{T,k,l}$ and $E_{T,k,l}$ is respectively coal-consumed volume and electric power of a thermal power-driven generator; $a_{T,k,l}$, $b_{T,k,l}$, $c_{T,k,l}$ is respectively coefficient of coal-consumed volume of a thermal power-driven generator.

The variation of coal-consumed volume is obtained by differentiating equation (25) with respect to $E_{T,j,i}$:

$$\Delta F_{T,k,l} = (2a_{T,k,l}E_{T,k,l} + b_{T,k,l})\Delta E_{T,k,l} \tag{12}$$

Coal-consumed volume increment rate is defined to be a ratio of the variation of the coal-consumed volume and the variation of electric power output of a coal-fired generator:

$$\lambda_{T,k,l} = \frac{\Delta F_{T,k,l}}{\Delta E_{T,k,l}} = 2a_{T,k,l}E_{T,k,l} + b_{T,k,l} \tag{13}$$

C. Optimal Scheduling for Electric Production

Water is one of renewable energy, which is an energy source that can be replenished in a short period of time, and is mainly used for electric energy production. Coal is non-renewable energy, which is an energy source that may be used up and cannot be recreated in a short period of time. In order to make as possible as best use of renewable resource, water must be placed on more prior consideration for electric energy production than coal. For this purpose, the objective of scheduling optimization of thermal-hydro power systems must minimize the water consumption volume consumed in electric energy production, including the water consumption volume consumed in hydro-electric plants and the water consumption volume exchanged from coal consumption volume consumed in coal-fired electric plants:

$$\min\sum_{t=1}^{T}[\sum_{j=1}^{N_H}\sum_{i=1}^{N_{HG}} W_{H,j,i} + \sum_{k=1}^{N_T}\sum_{l=1}^{N_{TG}} \gamma_{T,k,l}F_{T,k,l}] \tag{14}$$

where N_H and N_{HG} is respectively number of hydroelectric plants and hydro-driven generators in plant j, N_T and N_{TG} is respectively number of coal-fired electric plants and coal-fired generators, $\gamma_{T,k,l}$ is a coefficient exchanging coal consumption volume consumed in coal-fired electric plants into water consumption volume, and it is formulated:

$$\gamma_{T,k,l} = \frac{\lambda_{H,adv}}{\Delta F_{T,k,l} / \Delta E_{T,k,l}} \tag{15}$$

where $\lambda_{H,adv}$ is average water-consumed volume increment rate of all hydro-driven generators:

$$\lambda_{H,adv} = \frac{\sum_{j=1}^{N_H} \sum_{i=1}^{N_{HG}} \lambda_{H,j,i}}{N_H N_{HG}} \tag{16}$$

The constraint conditions include:

1) Equality constraint for electric power of thermal-hydro power systems: at any time t, the sum of the electric power produced by hydro-driven generators and coal-fired generators must be hold to be equal to load-demanded power:

$$\sum_{j=1}^{N_H} \sum_{i=1}^{N_{HG}} P_{H,j,i}(t) + \sum_{k=1}^{N_T} \sum_{l=1}^{N_{TG}} P_{T,k,l}(t) - P_L(t) = 0 \tag{17}$$

where $P_L(t)$ is load-demanded power at any time t.

2) Equality constraint for electric energy of thermal-hydro power systems: in the scheduling period T, the sum of the electric energy produced by hydro-driven generators and coal-fired generators must be hold to be equal to load-demanded energy:

$$\sum_{j=1}^{N_H} \sum_{i=1}^{N_{HG}} E_{H,j,i}(T) + \sum_{k=1}^{N_T} \sum_{l=1}^{N_{TG}} E_{T,k,l}(T) - E_L(T) = 0 \tag{18}$$

where $E_L(T)$ is load-demanded energy in the scheduling period T.

3) Inequality constraint for active and reactive power of hydro-driven generators:

$$\underline{P}_{H,j,i} \le P_{H,j,i} \le \overline{P}_{H,j,i} \tag{19}$$

$$\underline{Q}_{H,j,i} \le Q_{H,j,i} \le \overline{Q}_{H,j,i} \tag{20}$$

where $\underline{P}_{H,j,i}, \underline{Q}_{H,j,i}$ and $\overline{P}_{H,j,i}$, $\overline{Q}_{H,j,i}$ is respectively the lower and upper limited value of active and reactive power of hydro-driven generator i in plant j.

5) Inequality constraint for active and reactive power of coal-fired generators:

$$\underline{P}_{T,k,l} \le P_{T,k,l} \le \overline{P}_{T,k,l} \tag{21}$$

$$\underline{Q}_{T,k,l} \le Q_{T,k,l} \le \overline{Q}_{T,k,l} \tag{22}$$

where $\underline{P}_{T,k,l}, \underline{Q}_{T,k,l}$ and $\overline{P}_{T,k,l}$, $\overline{Q}_{T,k,l}$ is respectively the lower and upper limited value of active and reactive power of coal-fired generator l in plant k.

6) Inequality constraint for generation flow:

$$\underline{Q}_{G,j,i} \le Q_{G,j,i} \le \overline{Q}_{G,j,i} \tag{23}$$

Where $\underline{Q}_{G,j,i}$ and $\overline{Q}_{G,j,i}$ is respectively the lower and upper limited value of generation flow of hydro-driven generator i in plant j.

7) Inequality constraint for coal consumption volume:

$$F_{down,k} \le \sum_{l=1}^{N_{TG}} F_{T,k,l} \le F_{up,k} \tag{24}$$

where $F_{up,k}$ and $F_{down,k}$ is maximal limit and minimal limit of coal consumption volume of coal-fired electric plant k in the scheduling period T.

8) Inequality constraint for water consumption volume:

$$W_{down,j} \le \sum_{i=1}^{N_{HG}} W_{H,j,i} \le W_{up,j} \tag{25}$$

where $W_{up,j}$ and $W_{down,j}$ is maximal limit and minimal limit of water consumption volume of hydro-electric plant j in the scheduling period T.

IV. SIMULATING EXAMPLE AND RESULTS

In this paper, Guangxi electric power system including Hongshuihe hydroelectric stations in Hongshuihe river is taken for a studying example. The data for Hongshuihe hydroelectric plants and coal-fired electric plants in Guangxi electric power system is shown in Table I and Table II respectively. In the following section, three cases are given to illustrate the component and factor analytic method for optimal electric energy production of thermal power systems in one hour.

In high in-flow period, the reservoir inflow in each cascaded hydroelectric plant is assumed to be high. In this case, the water flow and water volume for electric energy production in each cascaded reservoir is available. Because of much more available water flow for electric energy production and smaller water-consumed volume in per unit electric energy output, the hydroelectric plants have much more superiority to be scheduled for electric energy production than coal-fired plants when the load is smaller.

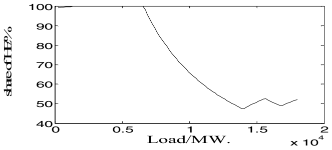

Figure 2. Sharing percentage of electric energy produced by hydro plants(HE: electric energy produced by hydro plants)

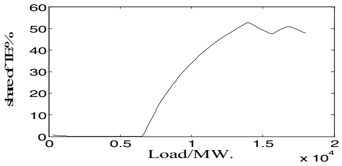

Figure 3. Sharing percentage of electric energy produced by coal-fired plants(TE: electric energy produced by hydro plants)

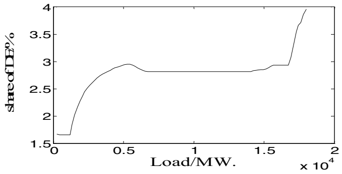

Figure 4. Sharing percentage of electric energy converted from water-deep pressure energy (DE: electric energy converted from water-deep pressure energy)

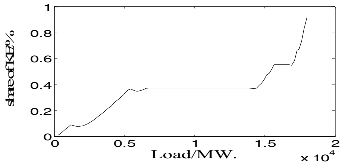

Figure 5. Sharing percentage of electric energy converted from kinetic energy (KE: electric energy converted from kinetic energy)

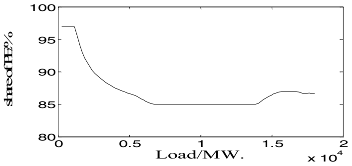

Figure 6. Sharing percentage of electric energy converted from potential energy (PE: electric energy converted from potential energy)

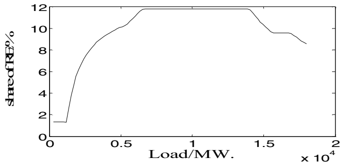

Figure 7. Sharing percentage of electric energy converted from reservoir energy (RE: electric energy converted from reservoir energy)

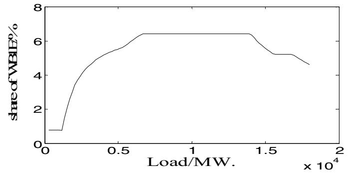

Figure 8. Sharing percentage of electric energy converted from reservoir energy in WB1 (WB1E: electric energy converted from reservoir energy in WB1)

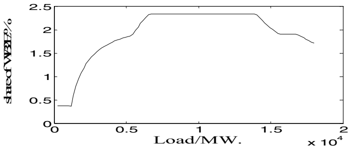

Figure 9. Sharing percentage of electric energy converted from reservoir energy in WB2

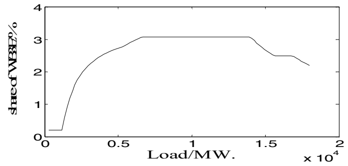

Figure 10. Sharing percentage of electric energy converted from reservoir energy in WB3

With increase in load, the percentage shared by hydroelectric plants increases, while the percentage shared by coal-fired plants decreases, as shown in Figure 2 and Figure 3. It is also seen that for small than about 7000MW of load, hydroelectric plants take 100% and coal-fired plants takes 0.

With increase in load, water-deep pressure energy and kinetic energy increases, as shown in Figure 4 and Figure 5, and potential energy decreases, as shown in Figure 7, while reservoir energy increases first and then decreases, as shown in Figure 7. It is also seen that these percentage retains constant from 7000MW to 14000MW.

Figure 1. With increase in load, the percentage of electric energy converted from reservoir energy of reservoir water body WB1, WB2 and WB3 included in the total electric energy produced by hydroelectric plants all increases, but retains constant from 7000MW to 14000MW, as shown in Figure 8-Figure 10.

V. CONCLUSION

Optimal schedule for electric energy production of thermal-hydro power systems depends on such factors as load demand, the water-consumed volume increment rate, the in-flow of reservoir, and so on. The plant with low water-consumed volume increment rate is first scheduled for electric energy production, and the plant with the highest water-consumed volume increment rate is finally scheduled for production.

The sharing percentage of the water-deep pressure energy, kinetic energy, potential energy and reservoir energy included in the total electric energy influenced by such factors as reservoir capacity, saved-water level, water head, water flow and so on. For load level varying from 6000MW to 18000MW, the sharing percentage of the water-deep pressure energy, kinetic energy, potential energy and reservoir energy varies respectively from 2.0% to 4.0%, 0.05% to 0.90%, 85.0% to 88.5%, 7.0% to 11.8%.

The percentage of electric energy converted from reservoir energy of reservoir water body WB1, WB2 and WB3 included in the total electric energy produced by hydroelectric varies with the load demand, but it's the highest value is about 6.0%, 2.0% and 3.0% respectively.

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References

[1] S. E. Fleten, S.W. Wallace, and W.T. Ziemba, "Portfolio management in a deregulated hydropower based electricity market," in *Proc.* 1997 *the3ird International Conf. on Hydropower Development*, pp. 197-204.

[2] S. E. Fleten, S. W. Wallace, and W.T. Ziemba, "Hedging electricity portfolios via stochastic programming," *IMA volumes on Mathematics and Its Applications,* vol. 128, pp. 71–93, 2002.

[3] Ilyas Eker, "The design of robust multi-loop-cascaded hydro governors," *Eng. Comput.* , vol.20, no.2, pp. 45–53, Mar. 2004.

[4] S. W. Wallace, and S.E. Fleten, "Stochastic programming models in energy," *The series Handbooks in Operations Research and Management Science,* vol. 10, pp. 637–677, 2003.

[5] X.Guan, A. Svoboda, and C. A. Li, "Scheduling hydro power systems with restricted operating zones and discharge ramping constraints," *IEEE Trans. Power Syst.*, vol. 14, pp. 126–131, Feb. 1999.

[6] J. S. Yang, N. Chen, "Short term hydrothermal coordination using multipass dynamic programming," *IEEE Trans. on Power Syst.*, vol. 4, pp. 1050–1056, Aug. 1989.