DETERMINATION OF OPTIMAL HYDRO GENERATING UNIT COMBINATION IN OPERATION

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Abstract: In this paper a method for determining the optimal combination of aggregates in a given hydropower plant is presented. As a specific case a hydropower plant with a proper number of installed hydro generating units is considered. Moreover, in this paper, the efficiency of the hydropower plant for all possible unit combinations in operation is determined. For this purpose the characteristic of efficiency of each unit is defined. The optimal unit combination is determined for all individual power ranges of the operating range of the plant.

Key words: Hydropower Plant, Efficiency Characteristic, Optimal Unit Combination.

1. INTRODUCTION

Of great importance for hydropower plant (HPP) operation is the achievement of the required electricity production at satisfactory efficiency of hydropower plant. To achieve maximum efficiency of a certain hydropower plant requires good knowledge of the operating modes of the plant and the number of production units in operation [1], [2]. On the efficiency of the hydropower plant, at particular power, affects the number of hydro generating units in operation. Therefore it is essential to consider the variation of the efficiency in various combinations of installed units, in order to achieve the required electricity production more efficiently.

For each particular load corresponds most favorable combination of hydro generating units that ensure maximum power plant efficiency. So, for each combination it is need to determine the power production interval which is best for hydropower plant to operate [3]. Operation of a certain hydropower plant should be such that the plant operates at ranges of high efficiency while ensuring minimal water consumption. Another problem is to determine the optimal amounts of generation power of the generating units, in operation, over the study period in order some given criteria to be fulfilled. In [5], the authors present an optimization solution to solve this problem for an actual plant, using Genetic Algorithms. While the paper [6] presents strategic planning for optimal operation of large hydroelectric power plants.

This paper presents a method for determining the optimal combination of hydro generating units to be put into operation in order to ensure maximum power plant efficiency in satisfying the specified load. This method we applied on hydro power plant with 4 installed units. For each possible combinations of available units, analytical and graphic, we determined the hydropower plant efficiency characteristic as a function of load. Further we determined which hydro generating unit combination provides the greatest power plant efficiency for certain operating power ranges. The method based on knowledge of the characteristics of the efficiency of installed units in HPP.

2. HYDROPOWER PLANT EFFICIENCY

The hydro generating unit efficiency is given by [4]:

$$\eta_j = \frac{P_{gj}}{P_{gj} + \Delta P_j} \tag{1}$$

where ΔP_j are active power losses in the j-th hydro generating unit, and P_{gj} is active generated power by the j-th hydro generating unit.

From the previous equation the active power losses in the j-th hydro generating unit can be expressed as [4]:

$$\Delta P_j = P_{gj} \frac{1-\eta_j}{\eta_j} \tag{2}$$

If n hydro generating units are in operation in the HPP, then the hydropower plant efficiency is determined by the expression:

$$\eta_e = \frac{P_{gv}}{P_{vv}} \tag{3}$$

where $P_{gv} = P_{g1} + P_{g2} + \ldots + P_{gn}$ is the total HPP power production, while $P_{vv} = P_{v1} + P_{v2} + \ldots + P_{vn}$ is the total HPP input power. By replacing in relation (3) the hydropower plant efficiency the following relation is obtained:

$$\eta_e = \frac{P_{g1} + P_{g2} + \ldots + P_{gn}}{P_{v1} + P_{v2} + \ldots + P_{vn}} \tag{4}$$

Taking into account the expressions (1) and (2) we obtained that:

$$\eta_e = \frac{P_{g1} + P_{g2} + \ldots + P_{gn}}{P_{g1} + \Delta P_1 + P_{g2} + \Delta P_2 + \ldots + P_{gn} + \Delta P_n} \tag{5}$$

or

$$\eta_e = \frac{P_{g1} + P_{g2} + \ldots + P_{gn}}{P_{g1} + P_{g1}\frac{1-\eta_1}{\eta_1} + P_{g2} + P_{g2}\frac{1-\eta_2}{\eta_2} + \ldots + P_{gn} + P_{gn}\frac{1-\eta_n}{\eta_n}} \tag{6}$$

Because the hydropower plant should meet a certain load *Pp*, then the n hydro generating units which are in operation is necessary to produce as much power as it has satisfied following relationship:

$$P_p = P_{g1} + P_{g2} + \ldots + P_{gn} \tag{7}$$

By replacing (7) in (6) for η_e we obtained that:

$$\eta_e = \frac{P_p}{\frac{P_{g1}}{\eta_1} + \frac{P_{g2}}{\eta_2} + \ldots + \frac{P_{gn}}{\eta_n}} \tag{8}$$

From the last expression can be noted that the determination of the hydropower plant efficiency η_e, at particular load of the plant *Pp*, it is necessary to know the efficiency of each of the generating units at their appropriate load.

The efficiency characteristic of hydro generating units that are installed in a particular HPP, commonly is modeled by polynomial of second order [1]:

$$\eta_j = \alpha \cdot P_{gj}^{\ 2} + \beta \cdot P_{gj} + \gamma \tag{9}$$

3. PRACTICAL EXAMPLE

In this section, analytically and graphically, the efficiency characteristic for each available combination of hydro generating units in given power range will be determined. Furthermore the optimal unit combination, which provides the highest efficiency, is determined for all individual power ranges of the plant power operating range. Microsoft Excel is used for calculation. The HPP which is analysed is consisting of 4 units whose efficiency characteristics are modeled by polynomial of second order.

The efficiency characteristic of unit 1 and unit 2 is graphically presented in figure 1 and is given by:

$$\eta_1 = -0{,}0000347 \cdot P_{g1}^{\ 2} + 0{,}0065922 \cdot P_{g1} + 0{,}588 \tag{10}$$

The efficiency characteristic of unit 3 and unit 4 is graphically presented in figure 2 and is given by:

$$\eta_3 = -4{,}6 \cdot 10^{-5} \cdot P_{g3}^{\ 2} + 0{,}003829 \cdot P_{g3} + 0{,}793482 \tag{11}$$

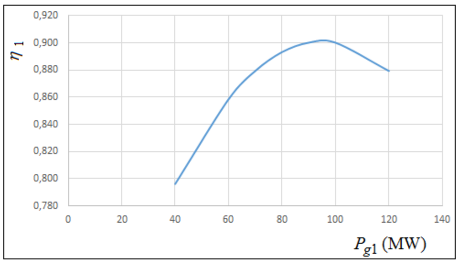

Fig. 1. Characteristic $\eta_1 = f_1(P_{g1})$

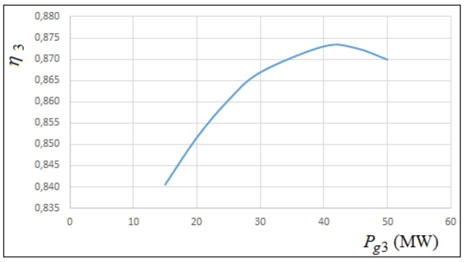

Fig. 2. Characteristic $\eta_3 = f_3(P_{g3})$

From the characteristics $\eta_1 = f_1(P_{g1})$ and $\eta_3 = f_3(P_{g3})$ it is noted that the minimum power output of the units 1 and 2 is $P_{g1m} = P_{g2m} = 40\,\mathrm{MW}$ and for unit 3 and 4 is $P_{g3m} = P_{g4m} = 15\,\mathrm{MW}$, while the maximum power output is $P_{g1M} = P_{g2M} = 120\,\mathrm{MW}$ and $P_{g3M} = P_{g4M} = 50\,\mathrm{MW}$. Thus the HPP total power operating range is $P_{g3m} = 15\,\mathrm{MW} \le P_P \le 2 \cdot P_{g1M} + 2 \cdot P_{g3M} = 340\,\mathrm{MW}$.

The possible combinations of units in operation are given in Table 1.

Table 1. Possible combinations of units in operation

Combination	***Unit 1***	***Unit 2***	***Unit 3***	***Unit 4***
1	*1*	*0*	*0*	*0*
2	*0*	*1*	*0*	*0*
3	*0*	*0*	*1*	*0*
4	*0*	*0*	*0*	*1*
5	*1*	*1*	*0*	*0*
6	*0*	*0*	*1*	*1*
7	*1*	*0*	*1*	*0*
8	*0*	*1*	*0*	*1*
9	*1*	*0*	*0*	*1*
10	*0*	*1*	*1*	*0*
11	*1*	*1*	*1*	*1*
12	*1*	*0*	*1*	*1*
13	*0*	*1*	*1*	*1*
14	*1*	*1*	*1*	*0*
15	*1*	*1*	*0*	*1*

Because the units 1 and 2, as well as the units 3 and 4 are with same characteristic the number of possible combinations of units in operation is reduced to 8 and are given in Table 2. According to the value of the efficiency for the combinations shown in Table 1 the combinations with the same efficiency are 1 and 2; 3 and 4; 7, 8, 9 and 10; 12 and 13; 14 and 15 respectively.

Table 2. Possible combinations of units in operation

Combination	***Unit 1***	***Unit 2***	***Unit 3***	***Unit 4***	***Sign***
1	*1*	*0*	*0*	*0*	*1A*
2	*0*	*0*	*1*	*0*	*1B*
3	*1*	*1*	*0*	*0*	*2A*
4	*0*	*0*	*1*	*1*	*2B*
5	*1*	*0*	*1*	*0*	*1A+1B*
6	*1*	*1*	*1*	*1*	*2A+2B*
7	*1*	*0*	*1*	*1*	*1A+2B*
8	*1*	*1*	*1*	*0*	*2A+1B*

For the combinations 1 and 2, from the Table 2, the efficiency characteristic is presented in figure 1 and 2 respectively ($\eta_{1A}=\eta_2=\eta_1=f_1(P_{g1})$ and $\eta_{1B}=\eta_4=\eta_3=f_3(P_{g3})$).

For the combinations 3, the efficiency characteristic $\eta_{2A}=f_{2A}(2\cdot P_{g1})=\eta_{1A}=f_1(P_{g1})$ is obtained by:

$$\eta_{2A}=-9\cdot 10^{-6}\cdot P_p^{\,2}+0.0033\cdot P_p+0.588,\ \text{for } 80\,\text{MW}\le P_P=2\cdot P_{g1}\le 240\,\text{MW} \quad (12)$$

and is presented in figure 3.

When in operation are the unit 3 and 4 (the combination 4) the efficiency characteristic $\eta_{2B}=f_{2B}(2\cdot P_{g3})=\eta_{1B}=f_3(P_{g3})$ is given by:

$$\eta_{2B}=-1\cdot 10^{-5}\cdot P_p^{\,2}+0.0019\cdot P_p+0.7935,\ \text{for } 30\,\text{MW}\le P_P=2\cdot P_{g3}\le 100\,\text{MW} \quad (13)$$

and is presented in figure 4.

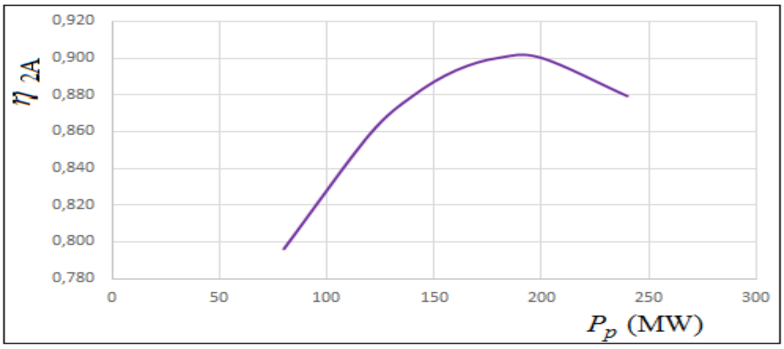

Fig. 3. Characteristic $\eta_{2A}=f_{2A}(P_p)$

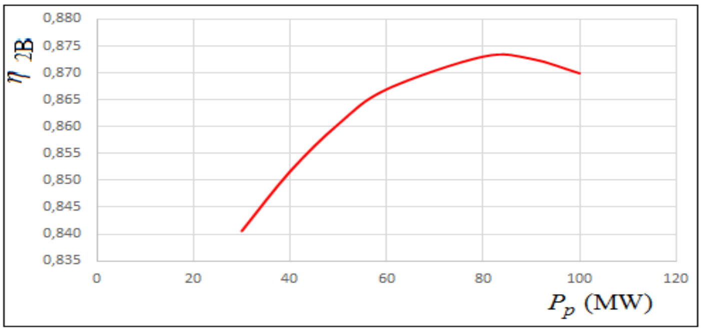

Fig. 4. Characteristic $\eta_{2B} = f_{2B}(P_p)$

When in operation are the unit 1(or 2) and 3(or 4), which corresponds to a combined 5 of Table 2, the efficiency characteristic can be obtained by:

$$\eta_{1A+1B} = \frac{P_p}{P_p + \frac{1-\eta_{1A}}{\eta_{1A}} \cdot P_{g1} + \frac{1-\eta_{1B}}{\eta_{1B}} \cdot P_{g3}} = \frac{P_p}{\frac{P_{g1}}{\eta_{1A}} + \frac{P_{g3}}{\eta_{1B}}} \quad (14)$$

for $P_{g1m} + P_{g3m} \le P_P = P_{g1} + P_{g3} \le P_{g1M} + P_{g3M}$

Specifically in our case, the efficiency characteristic of the combination 5 is graphically represented in Figure 5 and is determined by the following analytical expression:

$$\eta_{1A+1B} = -1.4 \cdot 10^{-5} \cdot P_p^2 + 0.00366 \cdot P_p + 0.6494 \quad (15)$$

for $55\,\text{MW} \le P_P = P_{g1} + P_{g3} \le 170\,\text{MW}$

When in operation are all 4 units (combination 6), the efficiency characteristic can be obtained by:

$$\eta_{2A+2B} = \frac{P_p}{P_p + 2 \cdot \frac{1-\eta_{1A}}{\eta_{1A}} \cdot P_{g1} + 2 \cdot \frac{1-\eta_{1B}}{\eta_{1B}} \cdot P_{g3}} = \frac{P_p}{\frac{2 \cdot P_{g1}}{\eta_{1A}} + \frac{2 \cdot P_{g3}}{\eta_{1B}}} \quad (16)$$

for $2 \cdot P_{g1m} + 2 \cdot P_{g3m} \le P_P = 2 \cdot P_{g1} + 2 \cdot P_{g3} \le 2 \cdot P_{g1M} + 2 \cdot P_{g3M}$

from which it follows that:

$$\eta_{2A+2B} = f_{2A+2B}(2 \cdot P_{g1} + 2 \cdot P_{g3}) = \eta_{1A+1B} = f_{1A+1B}(P_{g1} + P_{g3}) \quad (17)$$

Specifically in our case, the efficiency characteristic of the combination 6 is graphically represented in Figure 6 and is determined by the following analytical expression:

$$\eta_{2A+2B} = -3.43 \cdot 10^{-6} \cdot P_p^2 + 0.0018 \cdot P_p + 0.6494 \quad (18)$$

for $110\,\text{MW} \le P_P = 2 \cdot P_{g1} + 2 \cdot P_{g3} \le 340\,\text{MW}$

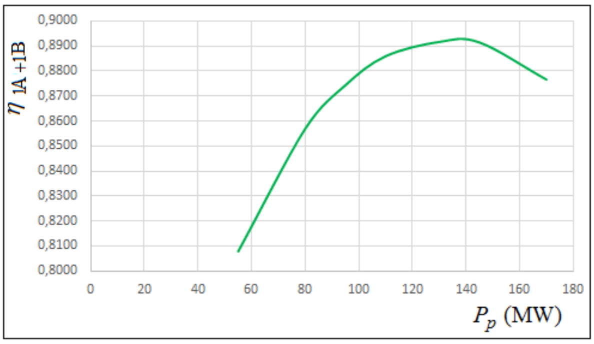

Fig. 5. Characteristic $\eta_{1A+1B} = f(P_p)$

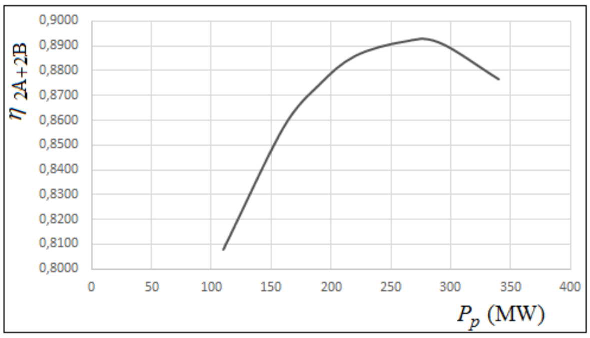

Fig. 6. Characteristic $\eta_{2A+2B} = f(P_p)$

For the combination 7, when in operation are the units 1 (or 2), 3 and 4, the efficiency characteristic can be obtained by:

$$\eta_{1A+2B} = \frac{P_p}{P_p + \frac{1-\eta_{1A}}{\eta_{1A}} \cdot P_{g1} + 2 \cdot \frac{1-\eta_{1B}}{\eta_{1B}} \cdot P_{g3}} = \frac{P_p}{\frac{P_{g1}}{\eta_{1A}} + \frac{2 \cdot P_{g3}}{\eta_{1B}}} \tag{19}$$

for $P_{g1m} + 2 \cdot P_{g3m} \le P_P = P_{g1} + 2 \cdot P_{g3} \le P_{g1M} + 2 \cdot P_{g3M}$

Specifically in our case, the efficiency characteristic of the combination 7 is graphically represented in Figure 7 and is determined by the following analytical expression:

$$\eta_{1A+2B} = -7 \cdot 10^{-6} \cdot P_p^{\ 2} + 0.0024 \cdot P_p + 0.6827 \tag{20}$$

for $70\,\text{MW} \le P_P = P_{g1} + 2 \cdot P_{g3} \le 220\,\text{MW}$

For the combination 8, when in operation are the units 1, 2 and 3 (or 4), the efficiency characteristic can be obtained by:

$$\eta_{2A+1B} = \frac{P_p}{P_p + 2\cdot\frac{1-\eta_{1A}}{\eta_{1A}}\cdot P_{g1} + \frac{1-\eta_{1B}}{\eta_{1B}}\cdot P_{g3}} = \frac{P_p}{\frac{2\cdot P_{g1}}{\eta_{1A}} + \frac{P_{g3}}{\eta_{1B}}} \quad (21)$$

for $2\cdot P_{g1m} + P_{g3m} \le P_P = 2\cdot P_{g1} + P_{g3} \le 2\cdot P_{g1M} + P_{g3M}$

In our case, the efficiency characteristic of the combination 8 is graphically represented in Figure 8 and is determined by the following expression:

$$\eta_{\ 2A+1B} = -5\cdot 10^{-6}\cdot P_p^{\ 2} + 0.0024\cdot P_p + 0.6241 \quad (22)$$

for $95\,\text{MW} \le P_P = 2\cdot P_{g1} + P_{g3} \le 290\,\text{MW}$

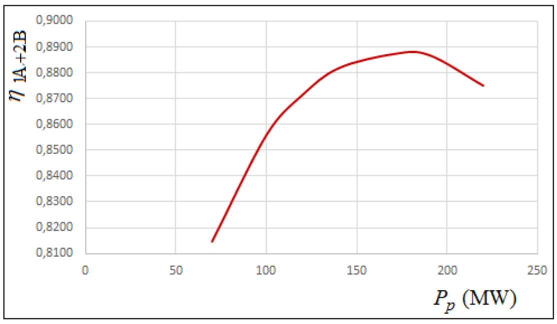

Fig. 7. Characteristic $\eta_{\ 1A+2B} = f(P_p)$

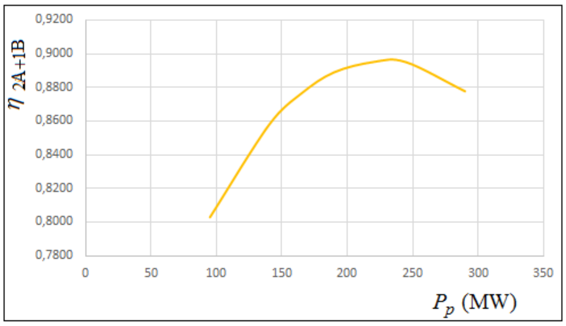

Fig. 8. Characteristic $\eta_{\ 2A+1B} = f(P_p)$

The optimal combination of units in operation, for certain power range, under the exposed method is that one that provides the highest efficiency. This problem could be easily solved if in the common graphic are presented the efficiency characteristic for all possible combinations given in Table 2. The HPP efficiency characteristic for all observed 8 combinations of aggregates, of the plant power operating range ($P_{g3m} = 15\,\text{MW} \le P_P \le 2 \cdot P_{g1M} + 2 \cdot P_{g3M} = 340\,\text{MW}$), is given on figure 9. From the results can be seen which unit combination provides the greatest plant efficiency for certain ranges of power.

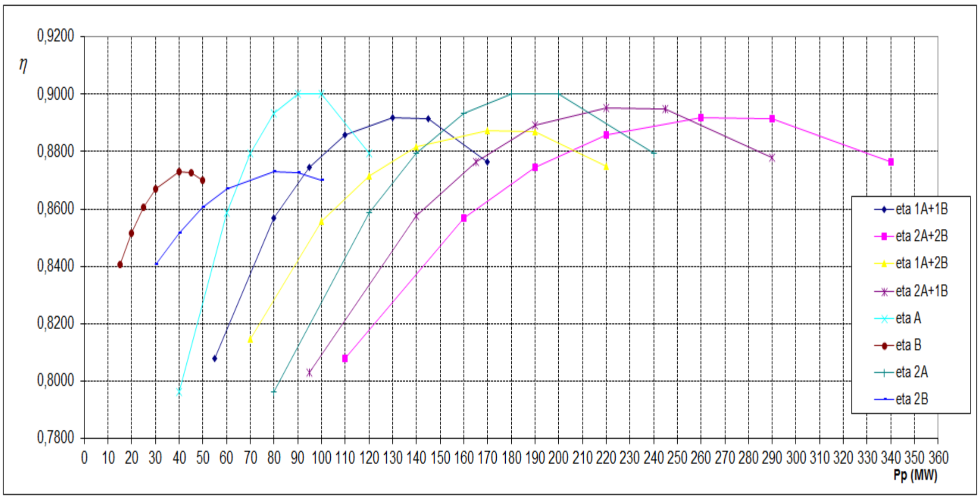

Fig. 9. Efficiency characteristic for all observed combinations of aggregates

4. CONCLUSION

This paper presents method for determining the optimal combination of hydro generating units to be put into operation in a hydro power plant, in order to ensure maximum power plant efficiency in satisfying the specified load. The method based on knowledge of the efficiency characteristics of each of the units installed in the plant. The method is applied to hydro power plant with 4 installed units. All possible combinations of units are considered and for each combination the efficiency as a function of load is obtained. From the presented graphic results, for the power operation ranges of certain unit combinations, the most favourable unit combination that meet the set criteria is established.

The HPP efficiency will have different values for different power distribution between hydro generating units. However for certain load of the HPP there is a specific power distribution between available units in which the HPP efficiency is maximized.

For future research can be solving the optimization problem aimed at determining the power distribution between the hydro units in which the HPP efficiency is the highest and met the appropriate operational constraints.

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