Optimal Computation of Small Hydropower Cluster Generation Based on River Topology

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Abstract. Small scale hydro-power (SHP) is clean, renewable, low-carbon and it is much more environmental protection than larger scale hydro-power. In remote mountainous regions with abundant water resources, adjacent small hydropower plants (SHP) are usually clustered to send out the electrical power. However, the power output of a SHP varies with the changes of water flow which brings challenges for both the reliability of power systems and power grid planning. Moreover, the generation state of SHP upstream will also cause the change of water flow downstream, which make the problem more complex. This paper proposes a method to reach the optimal generation of SHP cluster, considering the mutual influence of SHP in the river system. The correlation of water flow between different SHPPs is quantified based on river topology analysis. The classical genetic algorithm (GA) is used to compute the problem. A realistic system in Southeast China is studied to illustrate the feasibility of the proposed method.

1. Introduction

Hydropower, which has been developed for centuries, is one of the most widely used generation technologies. As a kind of renewable, clean and cost-efficient energy, hydropower has expanded greatly throughout the world since the early last century [1]. Nowadays, hydropower still supplies the majority of the world’s renewable electricity and the technically feasible potential of new development hydropower reaches about 1000 TWH per year globally [2].

Compared with large scale hydropower plants with large dams or reservoirs, the small scale hydropowers (SHP) are more environmentally friendly [3], which are commonly built in the run-of-river type to avoid deforestation, submergence and rehabilitation [4]. In addition, SHP achieves advantages of shorter gestation period and lower operational and maintenance costs [5]. In many remote rural or mountainous areas, particularly in the developing countries, SHP is considered as the most promising option for economic and sustainable power supply [6].

However, those remote rural or mountainous areas are usually in low-level electric power consumption. After balanced by the local loads, extra power outputs of SHP will flow into transmission grid. To reduce investments, several adjacent small hydropower plants (SHPP) are generally linked by one same transmission line or collected by a certain booster station. As a consequence, though the capacity of a single SHPP is no more than 30MW [7], the total power outputs of a SHP cluster may reach hundreds of megawatts.
Moreover, without a reservoir or only with a small one, a SHPP cannot maintain the stability of its power output. Actually, the water inflow keeps relatively stable in short term but varies quarterly. For example, the power outputs may be at the rated value in springs or wet seasons while it may be zero in cold winters or dry seasons. Considering the mentioned considerable capacity, the power volatility of SHP clusters could have serious impacts on the reliability of local or even outside power systems and it will also bring challenges for power grid planning.

Nevertheless, most of the existing studies focus on the large-scale hydropower with reservoirs, which are quite different from SHPPs. Relatively few research about SHP availability or reliability have been made, while some progresses still have been made. The generation availability of a single SHPP considering the uncertain of water inflow has been analyzed in [8], the water inflow was clustered into ten states to reduce the calculation. In [9], the impact of the combined integration of wind generation and SHPP on system reliability is explored. These works focus on one single SHPP or consider a SHP cluster is as one bigger SHPP. The co-relation of power generations between different SHPPs has not been considered, yet. Actually, in a SHP cluster, the water inflow of downriver SHPPs may be affected by the power generation of the upstream SHPPs. Therefore, the interaction of water inflow subject to river topology should be taken into consideration for SHP generation assessment, which demands further investigation.

This paper proposes a method to calculate the maximum electric power output of a SHP cluster, considering the mutual influence on generation of SHPP as the water flow downstream changes by the generation state of SHPP. The relationship of water flow about different SHPPs in the same river system is quantified based on river topology analysis. The classical genetic algorithm (GA) is used to solve problem. Simulations are performed on a realistic system in Southeast China to illustrate the feasibility of the proposed method.

2. Power Generation Model of a SHP Cluster

2.1. The power output Model of a SHPP
The SHPP consider here uses water potential energy to generate electric power, as shown in Fig. 1. For SHPP \( l \), the electric power output is determined by the inflow rate and the net head, and is given as follows

\[
P_l = 9.8 \rho H_l A_l Q_l
\]

where \( \rho \) is the density of water (1000kg/m\(^3\) at about 4\(^\circ\)C), \( H_l \) is the net head of the water (m), \( A_l \) is the efficiency of the generator and turbine, \( Q_l \) is the equipment flow (m\(^3\)/sec).

Usually, the net head is designed much higher than the depth of water, so the fluctuation of water depth can be ignored. Meanwhile, the efficiency of generator and turbine keep constant in a very large range [10], [11]. Thus, the power outputs of a SHPP depends on the water flow volume.

2.2. The topology between SHPPs in the same river system
In a river system, two rivers directly connect in two types: the confluence type or the diversion type, as shown in Figure 1. Any complex river system consists of these two basic types.

Ignoring the loss of the water flow, the changes of upstream affecting on downstream after another river flowing in or out still keeps the linear relationship, that is:

\[
\Delta Q_j = K_{ji} \Delta Q_i
\]

where \( \Delta Q_i \) is the flow increment at river \( i \) and \( \Delta Q_j \) is the increment at river \( j \) changed by \( \Delta Q_i \). \( K_{ji} \) is the connection coefficient. It will be 1 while the two rivers connect in confluence type, and a diversion ratio should be considered [12] while the two rivers connect in diversion type.
The generation status of SHPP upstream will change the downstream flow. A SHPP starts to work from outage status will bring a volume of $ΔQ_l$ decrement at the downstream of its intake and a volume of $k_lΔQ_l$ increment at the downstream of its tail race, and vice versa.

2.3. The maximum power output of a SHP cluster using genetic algorithm (GA) method

The status of a SHPP can be described by “0” and “1”. In this paper, $S_l=0$ means the SHPP $l$ turns off while $S_l=1$ means it turns on. The object of the work is to get the maximum power output of the SHP cluster:

$$P_{\text{max}} = \max P_\Sigma = \max 9.8\rho \sum_{j} S_j A_j H_j Q_j$$

The generation status of SHPP in the river system forms the chromosome coding in GA. The total power output decides the adaptability of a single chromosome, which is depending on the water flow. Moreover, the SHPP status will also affect the SHPP downstream. The flow chart shown in Figure 2 is the process to calculate the total power output in the cluster.

The step-by-step procedure to calculate the total power output of a SHP cluster while any of the SHPP in the system changes its generation state is shown as follows:

(a) If any of the SHPPs changes its state $S_l$, go to step b. Otherwise jump to step f.
(b) Calculate the flow increments at downstream of the intakes and the tail races.
(c) Calculate the downstream water flow changes using Eq. (2).
(d) If any of the water flow changes, go back to step c.

Figure 1. Graph of two rivers directly connected

Figure 2. Flow chart of Illustration of a river network
(e) Calculate the water flow at the intake for every SHPP.
(f) Calculate the total power output of a SHP cluster using Eq. (3).

3. Case studies and discussions

A SHP cluster in Southeast China is studied to illustrate the proposed methods. The system has 4 SHPPs and 10 hydro generators. Three SHPPs bring water from rivers, while the 3rd SHPP brings water from the tail race of the 2nd SHPP with a loss of 10%.

In this system, 1st SHPP and 2nd SHPP have three units while the 3rd SHPP and the 4th SHPP have two units. The intake of the 1st SHPP is from the river at point A while the tail race goes back to the river at point B. The 2nd SHPP is at downstream of the 1st SHPP, and its intake gets from the river at point C, while its tail race goes back to the river at point E. The intake of 3rd SHPP gets from the 2nd SHPP and its tail race goes back to the river system at point F. The 4th SHPP gets water from the river at point G and the tail race goes back to the river system at point H. The diagram of system is shown in Figure 3.

From the river topology in this case, it is showed that the generation of the 1st SHPP will not take effect on the other SHPPs, while the generation of the 2nd SHPP will directly affect the generation of the 3rd SHPP, both of whom will also affect the generation of the 4th SHPP.

The rated power, water flow and designed head of the hydro generators are shown in Table 1. The minimum water inflow is 50% of the rated inflow, and efficiency $A_i$ is considered as 80%.

| SHPP No. | Unit | Design head (m) | Rated power (MW) | Rated equipment flow (m$^3$/s) |
|----------|------|----------------|------------------|-----------------------------|
| 1 (A→B) | S1G1, S1G2 | 212 | 8 | 4.8 |
|  | S1G3 | | 4 | 2.4 |
| 2 (C→E) | S2G1, S2G2 | 38 | 5 | 16.7 |
|  | S2G3 | | 2.5 | 8.3 |
| 3 (D→F) | S3G1, S3G2 | 40 | 6.3 | 20.1 |
| 4 (G→H) | S4G1, S4G2 | 28 | 4 | 18.2 |
Three different situations are considered and the water-inflow at A, C and G with no SHPP working are shown in Table 2.

| State No. | Water inflow (m³/s) |
|-----------|---------------------|
|           | A       | C       | G       |
| 1         | 3.2     | 11.1    | 8.9     |
| 2         | 8.2     | 28.4    | 22.7    |
| 3         | 12.6    | 43.7    | 34.9    |

In this case, the unit capacities for a SHPP with three units are of 100%, 100% and 50%, respectively. And the unit capacities for a SHPP with two units are the same. Different water flow for the two types of SHPP are learned. It shows that the efficiency of SHPP with three units is better than those of two same capacity units. The available power output curves for SHPPs with different numbers of units are shown in Figure 4.

![Figure 4. Power-output curves for SHPPs with different numbers of units.](image)

Several solutions are got from GA and some of the best solutions are shown in Table 3.

| Water State No. | Schedule No. | Generation units | Total power output(MW) |
|-----------------|--------------|-------------------|------------------------|
| 1               | 1-1          | S1G1, S2G1        | 8.63                   |
| 2               | 2-1          | S1G1, S1G2, S2G1, S2G2, S3G1, S3G2, S4G1, S4G2 | 36.28 |
| 3               | 3-1          | All the units     | 53.1                   |
| 3               | 3-2          | All except the units of SHPP 3 | 40.17 |

In the first water state, the best schedule for generation is to turn on a 8MW unit of the 1st SHPP and a 5MW unit of the 2nd SHPP, and the maximum power output of the system is 8.63MW. In the second water state, the best schedule for generation is to turn on all the units except the 4MW unit of the 1st SHPP and the 2.5MW unit of the 2nd SHPP, and the maximum power output of the system is 36.28MW. In the third water state, the best schedule is to turn on all the units and the the maximum power output of the system is 53.1MW. The unavailable of the 3rd SHPP is considered in the third case, which show the unavailable of the 3rd SHPP will affect on the 4th SHPP with 0.33MW decrement.

### 4. Conclusions and Outlook

This paper has provided a method to calculate the maximum electric power output of a SHP cluster. The mutual influence between SHPPs is considered based on river topology analysis and the classical genetic algorithm (GA) is used to solve problem. Based on the simulation results on a ten-generator SHP cluster in Southeast China, the following conclusions can be made:

- The optimal generation of a SHP cluster depends on the water situation, and it is totally different between wet seasons and dry seasons.
- The efficiency of SHPP with three units is better than those of two same capacity units.
- The optimal generation of a SHPP will be affected by the generation state of the SHPPs upstream, especially the one directly utilizing water from other SHPPs. However, further research is needed in the future. For example, the optimal generation of SHP cluster is described as a 0-1 planning problem and the power output calculation is also very complex which makes the problem even more difficult. In the future, we will go deep into the co-relation of SHPPs and try to find a method to simplify the calculation. Also, we will also consider the ecological water supply in future.

Acknowledgments
This work is supported by the China NSFC under Grant 61801431 and the Zhejiang Provincial Department of Water Resources under Grant RC1822 and RC1815.

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