Evolutionary Game Analysis of Water Resources Conflict for Cascade Hydropower Stations in Multiple Power Generation Subjects

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Abstract—Against the incomplete information in the basin hydropower cascade system and bounded rationality of the behaviors of market subjects and through the analysis of competition and cooperation between the different interest groups of the river basin cascade hydropower stations, the dynamics model of evolutionary game is used to study the "tragedy of the commons" and compensation mechanism concerning the conflicts of different owners of the cascade hydropower stations for the realization of Pareto optimal equilibrium conditions under incomplete information and bounded rationality, so as to provide the decision-making support to optimized operation of the hydropower cascade system under market environment.

Keywords-Evolutionary Game Analysis; Optimization; Cascade Hydropower; Water Resources; Conflict

I. INTRODUCTION

To the different interest groups of the river basin cascade hydropower stations which the available water resources are limited, owing to the upstream hydroelectric stations have the priority of storage, so the stations have little attractive and incentive to operate jointly, as a consequence, the cascade hydropower stations have to realize independent operation, and the basin's overall efficiency is not optimal. It is not disadvantage of to make full use of limited water resources. How to make water strategy of the different interest groups of the river basin cascade hydropower stations to maximize comprehensive benefit has become an urgent problem. Evolutionary game theory [1, 2] is an effective tool to solve the problem, and it successfully solves the problem of water resources allocation on river basin level under different water right modes[3,4], competitive urban water supply enterprises[5], water resources management under water shortage condition[6], the game of efficiency multi-agent power plants[7], interest conflict of river basin ecological compensation[8], regional ecological cooperation[9,10]. The paper analyses the water resources utilization conflict of the different interest groups of the river cascade stations by adopting the replicator dynamics model of evolutionary game, the research results hopes to offer decision-making's basis and reference for the river basin management organizations.

II. ANALYSIS ON THE CONFLICT OF UTILIZING WATER RESOURCES OF CASCADED HYDROELECTRIC STATIONS IN THE TRAGEDY OF THE COMMONS

For the different interest groups of the river basin cascade hydropower stations, the basin limited water resources in the amount of water is a public resource, the nature of the public property. They will be arranged in accordance with the principle of self-interest to maximize generation scheduling is based on the complete rationality to take advantage of the limited amount of water, but in reality, the Cascade Hydropower completely rational is difficult be met, often manifested as bounded rationality, and incomplete information between the basin power plants, especially for limited regulating ability of the downstream cascade power stations, in the arrangements for power generation, the plan is largely dependent on the level of understanding of the generation scheduling of upstream hydroelectric stations. Therefore, the different interest groups of the river basin cascade hydropower stations in the limited basin water resources utilization conflict performance on one game, unlike the fully rational case as the beginning will be able to directly achieve Nash equilibrium Nash equilibrium. This requires a learning exchange and the process repeated games, in order to constantly improve the level of basin power plants rational and accordingly adjust its generation strategies, and the

mutual cooperation between the basin cascade hydropower stations, thereby reducing basin water resources utilization conflict, to maximize the efficiency of water resources utilization.

We assume that the two groups different interest cascade hydropower stations with similar size is located in the upper reaches as player 1, located downstream cascade hydropower stations (group) is as play 2. There are two different strategies in each game participant, that cooperation and non-cooperation, participants in any randomly selected by two watershed game. When the game participants to choose cooperation strategy, they are the largest basin cascade total generating effective to arrange for the target each generation water plan, select uncooperative places its own power generation benefits arrangements generation water plan. Unequal status due to the upstream and downstream power station, we assume:

If all cascade hydropower stations adopt a cooperative strategy, they execute the compensation operation of cascade hydropower stations to maximize total generating benefits of the river basin. The two game players gains were A and B, the cascade of total receipts at this time (A + B) Max.

If two game players adopt uncooperative strategy, they execute the generating scheduling based on its own maximizing generating benefit. Upstream power station occupies a fully active in the arrangements for power generation water plan, and then made the biggest gains C. Because upstream hydropower stations is uncooperative, downstream hydropower stations cannot fully understand the generating plan of upstream hydropower stations, and the downstream hydropower stations will not be able to accurately predict inflow runoff. So the downstream hydropower stations only arrange the generating plan to maximize its own generating benefits in most adverse runoff, and this income is D.

When upstream hydropower stations take cooperation strategy, the upstream power stations arrange the generating plan to maximize cascade generating benefits, and the downstream power plant to fully understand its generating plan, the downstream stations there is only adopt a cooperative strategy to arrange effective generating plan to maximize its own generating benefits and cascade generating benefits.

When the upstream stations select uncooperative strategy and downstream stations choose cooperation strategy, the upstream stations arrange generating plan based on maximizing its own generating benefits and achieve maximum income C at this time. Because downstream station cannot understand the generating plan of upstream stations and only arrange the generating plan to maximize its own generating benefits in most adverse runoff, and this income is E. Gains matrix is shown in Table 1.

TABLE I.   GAINS MATRIX

		Player 2	
		cooperative	uncooperative
Player 1	cooperative	A, B	A, B
	uncooperative	C, E	C, D

From the above analysis we can see, the relationship

of the income is C> A, B> D> E, A + B> C + D> C + E.

Assuming the replicator dynamics game involving a large group of bounded rationality water users in basin, it is impossible to find the best strategy at the start of game: (cooperation, cooperation). Some of the water users with limited rationality may take "cooperation" and some "non-cooperation", and the strategies are not given in advance. The strategies of the water users will be adjusted with the learning process. Assuming the ratio of "cooperation" in upstream stations games is x, thus the ratio of "non-cooperation" is $1-x$. The ratio of "cooperation" in downstream stations games is y, thus the ratio of " non-cooperation " is $1-y$.

The expected profits of the players in upstream stations and the average income of the groups were:

$$\pi_1^C = y \times A + (1-y) \times A$$
$$\pi_1^{NC} = y \times C + (1-y) \times C$$
$$\overline{\pi_1} = x \times \pi_1^C + (1-x) \times \pi_1^{NC} = x \times A + (1-x) \times C$$

The expected profits of the players in downstream stations and the average income of the groups were:

$$\pi_2^C = x \times B + (1-x) \times E$$
$$\pi_2^{NC} = x \times B + (1-x) \times D$$
$$\overline{\pi_2} = y \times \pi_2^C + (1-y) \times \pi_2^{NC}$$
$$= (D-E) \times xy + (1-D) \times y + (B-D) \times x + D$$

The replicator dynamics differential equations of the game problem are as follows:

$$\frac{dx}{dt} = x \times (\pi_1^C - \overline{\pi_1}) = x(1-x)(A-C)$$

$$\frac{dy}{dt} = x \times (\pi_2^C - \overline{\pi_2}) = y(1-y)(1-x)(E-D) \qquad (1)$$

$$(2)$$

Result in:

$$F(x) = x \times (\pi_1^C - \overline{\pi_1}) = x(1-x)(A-C)$$
$$F(y) = x \times (\pi_2^C - \overline{\pi_2}) = y(1-y)(1-x)(E-D)$$

The replicator dynamics differential equations (1) show that, $x^* = 0$ and $x^* = 1$ are steady state, and are independent of y. Because $F'(x)|_{x=0} = A - C < 0$ and $F'(x)|_{x=1} = C - A > 0$. By the stability theory of differential equations, $x^* = 0$ is the evolutionary the stable strategy of upstream stations players.

Similarly, if $x=1$, all y are steady state, that is, when the upstream stations players choose cooperation strategy, the incomes of downstream stations with choosing any strategy are same. When $x < 1$, $y^* = 0$ and $y^* = 1$ are steady state. For $F'(y)|_{y=0} = (1-x)(E-D) < 0$, $F'(y)|_{y=1} = (1-x)(D-E) > 0$, $y^* = 0$ is steady evolutionary strategy. The dynamic changes of y are shown as Figure 1.

As can be seen by the above analysis:

Due to joint optimal dispatching with maximizing cascade generation benefit lack reasonable compensation mechanisms to upstream stations, so the upstream stations don't want to take joint optimal

dispatching. Therefore it is difficult to effectively implement joint optimal dispatching of cascade hydropower stations. On the one hand, basin's limited water resources are not fully utilized, and it is the disadvantage to the sustainable development of the basin; On the other hand, the upstream stations arrange generating plan with the principle of maximizing their own income, and did not consider other downstream power station interests, so that the water conflicts and contradictions of downstream and upstream will further exacerbate and intensify, it is the disadvantage to the sustainable development of the basin. Nash equilibrium of water conflicts game model with a completely non-cooperative state of basin cascade hydropower stations is inefficient. Therefore, based on the requirements of the scientific concept of development, watershed management agencies unified schedule basin water resources is very necessary.

III. WATER RESOURCES CONFLICT FOR CASCADE HYDROPOWER STATIONS UNDER COMPENSATION MECHANISM

Once the water resources of the river basin is decided, every party's interest will be definitely involved in the utilize extent of the water resources in the upstream and downstream hydroelectric stations. Therefore, the participation of the river basin management organization to build up reasonable system of paid use of water and cascade hydropower compensation distribution mechanism are the effective ways to coordinate the using conflict and contradictory of water resources, which not only encourages the upstream hydroelectric stations work to maximize efficiency, but also sets a limit on upstream hydroelectric stations' immoderation of water storage.

Though the upstream hydroelectric stations have the priority of water storage, they have no motivation and initiative to distribute water for the midstream and downstream hydroelectric stations. Upstream hydroelectric stations will get the maximum economic benefit, but the downstream stations inefficiently utilize of water resources, and water resources for industry, agriculture and environment in the midstream and downstream hydroelectric stations cannot be lack. Herein, the river basin management organization will take certain strategies to make the upstream hydroelectric stations to take notice of the electricity-generate benefits of the downstream hydroelectric stations and the overall social benefits of the whole downstream area.

The control behavior of the river basin management organization on benefit reflects the involvement of penalty factor. While they do not cooperate, the upstream hydroelectric stations' punishment on benefit will be α, the downstream hydroelectric stations' will be β. Herein, the river basin management organization will take the strategy of

compensation for the beneficiary. Provided the manager takes the strategy through proper institutional arrangement to make the downstream hydroelectric stations responsible for the loss that appears when the upstream hydroelectric stations try to meet the maximum benefit of the whole basin. Namely, the downstream hydroelectric stations take out ε from the increased benefits generated by the joint dispatching to compensate the upstream hydroelectric stations, which is good for the basin to participate in the choose of Pareto equilibrium strategies.

Game structure change in cascade hydropower stations water distribution, as is shown in table 1.

TABLE II.   PAY OFF MATRIX

| | | Player 2 | |
		cooperative	uncooperative
PlPayer 1	cooperative	$A+\varepsilon , B-\varepsilon$	$A+\varepsilon , B-\varepsilon-\beta$
	uncooperative	$C-\alpha , E$	$C-\alpha , D-\beta$

Likewise, the ratio of the upstream hydroelectric stations choose "cooperation" is x, the ratio of "noncooperation" is $1-x$; the ration of the downstream hydroelectric stations choose "cooperation" is y, the ratio of "noncooperation" is $1-y$.

The expected profits of the players and the average profits of the group of the upstream hydroelectric stations are:

$$\pi_1^C = y\times(A+\varepsilon)+(1-y)\times(A+\varepsilon)$$
$$\pi_1^{NC} = y\times(C-\alpha)+(1-y)\times(C-\alpha)$$
$$\overline{\pi_1} = x\times\pi_1^C+(1-x)\times\pi_1^{NC}=(A+\varepsilon-C+\alpha)x+(C-\alpha)$$

The expected profits of the players and the average profits of the group of the downstream hydroelectric stations are:

$$\pi_2^C = x\times(B-\varepsilon)+(1-x)\times E$$
$$\pi_2^{NC} = x\times(B-\varepsilon)+(1-x)\times(D-\beta)$$
$$\overline{\pi_2} = y\times\pi_2^C+(1-y)\times\pi_2^{NC}$$
$$= (D-E)\times xy+(E-D+\beta)\times y+(B-D-\varepsilon)\times x+(D-\beta)$$

the replicator dynamics differential equations of the game:

$$F(x) = x\times(\pi_1^C-\overline{\pi_1})=x(1-x)[(A+\varepsilon)-(C-\alpha)] \quad (3)$$
$$F(y) = x\times(\pi_2^C-\overline{\pi_2})=y(1-y)(1-x)[(E-D)x-(E-D+\beta)]$$
$$(4)$$

From equation (3):

（1）When $A+\varepsilon=C-\alpha$, whatever the strategy the upstream hydroelectric stations take, their benefits will be the similar with the downstream hydroelectric stations.

（2）When $A+\varepsilon>C-\alpha$, namely the benefits that the upstream hydroelectric stations take the "cooperation" strategy is greater than that of taking the "noncooperation" strategy, $x^*=1$ makes the benefits of both party similar.

（3）When $A + \varepsilon < C - \alpha$, namely the benefits that the upstream hydroelectric stations take the "cooperation" strategy is smaller than that of taking the "noncooperation" strategy, $x^* = 0$ makes the benefits of both party similar.

From equations 4 to 7, we know

（1）When $x = \dfrac{(D - \beta) - E}{D - E}$, whatever strategy the downstream hydroelectric stations take, the benefit will be the same. When we do not take account of the punishment of the upstream hydroelectric stations' noncooperation, $x = 1$, namely when the upstream hydroelectric stations take the "cooperation" strategy, whatever strategy the downstream hydroelectric stations take, their benefit is similar. When $E = D - \beta$, $x = 0$, namely the upstream hydroelectric stations take the "noncooperation" strategy, the downstream hydroelectric stations benefit the same whether cooperate or not.

（2）When $1 > x > \dfrac{(D - \beta) - E}{D - E}$, $y^* = 1$ is the evolutionary stable strategy, namely the downstream hydroelectric stations take cooperation strategy to makes the benefits of both party similar.

（3）When $0 < x < \dfrac{(D - \beta) - E}{D - E}$, $y^* = 0$ is the evolutionary stable strategy, namely the downstream hydroelectric stations take cooperation strategy to makes the benefits of both party similar.

The dynamic change of y is shown in the following pattern. Form the pattern 2, we know that when $\beta = 0$, the downstream hydroelectric stations will take the "noncooperation" strategy; when $E = D - \beta$, the downstream hydroelectric stations will take the "cooperation" strategy.

From the above analysis we know:

Once the aggregate water resources of the basin is decided, every party's interest will be definitely involved in the utilize extent of the water resources in the upstream and downstream hydroelectric stations. Therefore, the involvement of the river basin management organization is the effective way to complete the water resources allocation.

The river basin management organization build up the reasonable compensation mechanism, which take out part of the increased benefit created by joint dispatching from the downstream hydroelectric stations to compensate for the upstream hydroelectric stations, to make the benefit of the upstream hydroelectric stations is greater than sole dispatching. The upstream hydroelectric stations have the motivation and initiative to take the cascade joint dispatching to attain the optimal Pareto and increase the use ratio of the limited water resources in the river basin.

In the meantime, the river basin management organization arouses the notice of the upstream hydroelectric stations towards the overall social benefits of the whole downstream area, such as ecology, environment, irrigation and domestic and industrial water, to give up properly the priority of using water through penalty factor, which plays a key role in the control behavior of the river basin management organization.

When the maximum benefits of the upstream hydroelectric stations taking noncooperation strategy minus the punishment by the river basin management organization is smaller than the benefits created by cooperation, the upstream hydroelectric stations will take the cooperation strategy. Because the upstream hydroelectric stations have the priority to water storage, therefore its strategy has nothing to do with the downstream hydroelectric stations. In the meantime, the downstream hydroelectric stations have to take the cooperation strategy to get the maximum benefit, which bring the greatest overall benefit to the whole river basin. The strategy of the downstream hydroelectric stations rely on the upstream hydroelectric stations, therefore, the river basin management organization can choose the "cooperation, noncooperation" strategy which enable the river basin to get the optimal overall benefit and attain the goal of optimal water resources allocation through the adjustment of the parameters ε and β.

IV. CONCLUSIONS

The river basin water resources has the characteristic of public which enables the owners in both the upstream hydroelectric stations and the downstream hydroelectric stations behave in their own thought without the intervention of the river basin management organization, as a result, the limited water resources could not be fully utilized. Therefore, it is necessary to enhance river basin management and build up reasonable compensation mechanism. We can draw the following conclusion from the above game analysis aimed at water resources allocation in the river basin.

(1) Based on the public character of the water resources, the water resources in the river basin have to be cooperatively utilized by the upstream and downstream hydroelectric stations and be managed cooperatively by the whole river basin.

(2) The necessity of being liable to the rational behavior of noncooperation of the individual and the possibility of achieve the rational behavior of cooperation of the collective exist in the cascade water resources allocation.

(3) The joint dispatching between river cascades could not realize through self adjustment, but can only realize through the control and compensation of the river basin management organization.

(4) The behavior choose of the river cascade hydroelectric stations is various, which should balance the function of encouragement and control reasonably to better exert the comprehensive coordinate functions of the river

basin management organization and government functional departments.

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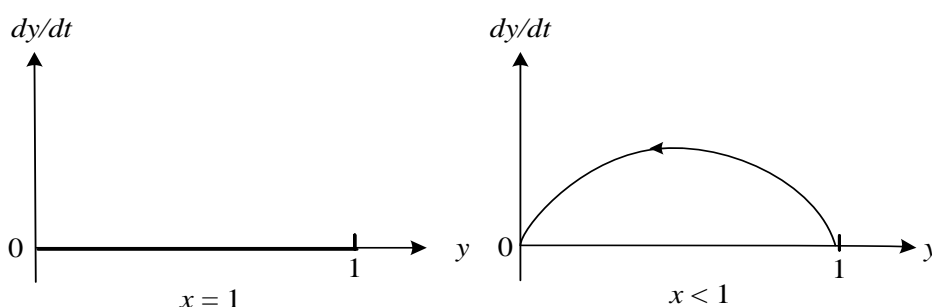
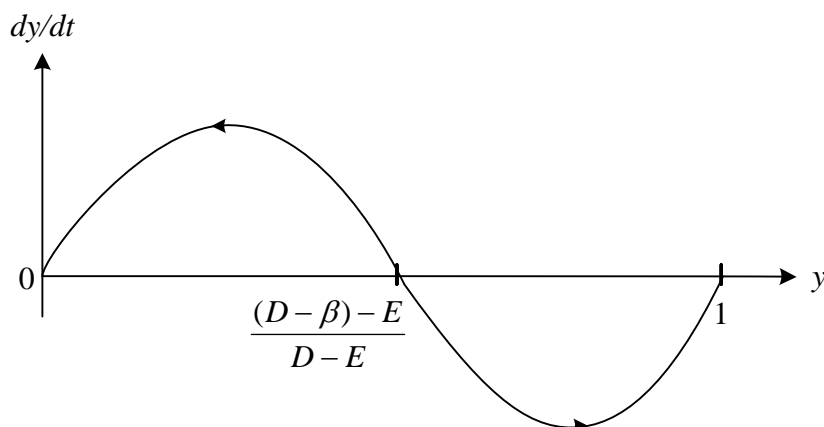Figure 1.   Group replicated dynamic phase diagram of player 2.

Figure 2.   Group replicated dynamic phase diagram of Player 2.