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Two Stage Particle Swarm Optimisation for Long-term Operation of a Hydroelectric Power System

The problem of determining the optimal long-term operation of a hydroelectric power system has been the subject of numerous publications over the past sixty years. A major problem encountered in operating long-term hydroelectric power system is their dimensionality. A great effort to decrease or eliminate possibility of dimensionality problem is addressed through developing innovative optimisation techniques, such as genetic algorithms, artificial neural networks, and so on. Particle swarm optimisation (PSO), a newly developed evolutionary technique, is a population based stochastic search technique with reduced memory requirement, computationally effective and easily implemented compared to other evolutionary algorithm. However, there exist some difficulties in applying PSO to hydropower system. Constrained by complex constraints and hydraulic relationships between upper and lower reservoirs, it is unfeasible to use stochastic search algorithms of PSO directly for most initial populations. In this paper, a two stage PSO algorithm is presented to solve the optimal long-term operation of a hydroelectric power system. The maximisation of electricity generation and maximisation of minimal mean power of the hydropower system are alternatively used as the objective of long-term planning of hydroelectric power for the two stage problem. The maximisation of minimal mean power of the hydropower system is chosen as the objective at the first stage and an initial feasible solution will be generated using PSO. The system objective, ie the maximisation of electricity generation is selected as the objective at the second stage and the optimal result of the first stage will be used as the initial feasible solution. The proposed method is implemented to the optimal long-term operation of a hydroelectric power system in the Yunnan Power Grid which is located in the Yunnan Province of China and consists of 17 dominated hydropower plants with an installed capacity of 3,942.5 MW. The results show that the two stage PSO can give reasonable and efficient solution and that applying PSO to the long-term operation of a hydroelectric power system is feasible.

Keywords: *Particle Swarm Optimisation, Long-tem Operation, Hydroelectric Power System, Large-scale Optimisation*

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Introduction

The problem of determining the optimal long-term operation of a hydroelectric power system has been the subject of numerous publications over the past sixty years (Turgeon A, 1981; Yeh WWG, 1985; Saad M *et al.,* 1994; Keppo J, 2002; Barros MTL *et al.,* 2003; Huang *et al.,* 2003). Yet no completely satisfactory solution has been obtained because the optimal operation of hydroelectric power system is a sort of complicated, multi-dimension and nonlinear global optimisation problem. A major problem encountered in operating long-term hydroelectric power system is their dimensionality. Many classical methods have been used to solve the long-term operation of a hydroelectric power system, including dynamic programming successive approximations (DPSA), incremental dynamic programming (IDP), discrete differential dynamic programming (DDDP) (El-Awar *et al.,* 1998; Mahmoud M, 2004) and aggegation-decomposition (Saad M *et al.,* 1994; Turgeon A and Charbonneau R, 1998), which are proposed to surmount the dimensionality problem for multi-reservoir system (Labadie, 2004; Yurtal R, 2005). Recently, a great effort to decrease or eliminate possibility of dimensionality problem is addressed through developing innovative optimisation techniques of heuristic programming (HP) methods. The HP-based techniques for the complex reservoir system have overcome some of the shortcomings of mathematical programming (Labadie, 2004; Teegavarapu and Simonovic, 2002). Among HP-based techniques, evolutionary computation has received more interest because of its ability to find the global optimum, flexibility in dealing with complex systems and simplicity in implementation. The genetic algorithm is a general-purpose stochastic and parallel search method based on the mechanics of natural selection and natural genetics. As a search, it has the potential to obtain near-global minimum, and has the capability to obtain accurate results within a short time with constraints easily included. It is a population search method that has been successfully applied to many complicated optimisation problems of water resources (Cheng *et al.,* 2002, 2005, 2006; Huang *et al.,* 2002; Kuo *et al.,* 2003; Akter and Simonovic, 2004; Chang *et al.,* 2005; Reis *et al.,* 2005; Chen, 2006; Mousavi SJ, 2004). Nevertheless, some deficiencies in GA performance, including premature convergence or a slow convergence process have been also identified (Eberhart and Shi, 1998).

As a new evolutionary optimisation technique developed by Kennedy *et al.* (Kennedy and Eberhart 1995; Kennedy *et al.,* 2001), particle swarm optimisation (PSO) simulates the social behavior of birds flocking for a desired place. PSO is distinctly different from other evolutionary-type methods in a way that it does not use the filtering operation, and the entire population is maintained through the search procedure so that information is socially shared among individuals to direct the search towards the best position in the search space. PSO is a population based stochastic search technique with reduced memory requirement, computationally effective and easily implemented compared to other evolutionary algorithm. In the field of water resources, a few applications of PSO have been reported recently (Chau, 2006; Gill *et al.,* 2006; Jung and Karney, 2006) and are providing to be efficient algorithms for solving hard optimisation engineering problems.

Recently, Labadie (2004) presented in-depth and excellent reviews of heuristic programming models for water resources problem, especially for GAs. It has been pointed out that a disadvantage of GAs is the difficulty of explicitly accounting for constraints and maintaining feasible solutions in the population. GAs must be modified for each new application (Labadie, 2004). Similar to GAs, a disadvantage of PSO is the difficulty of maintaining feasible solutions in the population for problems with complex constraints during stochastic search procedure. Especially for hydroelectric power system, most of initial populations are unfeasible using the stochastic search algorithms of PSO constrained by the complex constraints and hydraulic relationships between upper and lower reservoirs. A specific strategy of using PSO for this problem is required. In this paper, a two stage PSO algorithm is presented to solve the optimal long-term operation of a hydroelectric power system. The maximisation of electricity generation and maximisation of minimal mean power of the hydropower system are alternatively used as the objective of long-term planning of hydroelectric power for the two stage problem. The maximisation of minimal mean power of the hydropower system is chosen as the objective at the first stage and an initial feasible solution will be generated using PSO. The system objective, ie, the maximisation of electricity generation is selected as the objective at the second stage and the optimal result of the first stage will be used as the initial feasible solution.

The major contribution of this work is to introduce a case example of modifying PSO procedure to adapt the complex optimisation engineering problem. The two stage PSO algorithm can randomly generate feasible solutions satisfying all the system constrains at all time periods.

The proposed method is implemented to the hydroelectric power system of the Yunnan Power Grid which is located in the Yunnan Province of China and consists of 17 dominated hydropower plants with an installed capacity of 3,942.5 MW. The results show that two stage PSO can give reasonable and efficient solution and applying PSO to the long-term operation of a hydroelectric power system is feasible.

Problem Formulation for Hydroelectric Power System

Objective Function

Multi-reservoir power system operation can be characterised by various objectives and constraints. The choice of objective is dependent on planning and operational goals. Traditionally, maximisation of electricity generation and maximisation of minimal mean power of the hydropower system are often used as the purpose of long-term planning of hydroelectric power. In this paper, maximisation of electricity generation is chosen as the system objective. The objective function can be expressed as

$$\text{Max} \quad E = \max \sum_{t=1}^{T}\sum_{i=1}^{N} p_{it}\, \Delta_t \tag{1}$$

where p_{it} = mean power of ith station during period t; Δ_t = time step; T = length of the operational time horizon; N = number of stations; E = electricity generation of hydropower reservoir system.

Constraints

Eqn (1) is subjected to the following constraints:

Mass balance equation for reservoir storages and inflows is

$$V_{i,t+1} = V_{i,t} + (q_{i,t} - Q_{i,t} - S_{i,t})\Delta_t \tag{2}$$

where $V_{i,t}$ and $V_{i,t+1}$ are initial and final storage volumes of ith station during period t; $q_{i,t}$ is inflow into the reservoir; $Q_{i,t}$ is discharge for hydropower generation; $S_{i,t}$ is total release for flood, irrigation and other goals.

Maximum and minimum storage at all reservoirs

$$\mathrm{Min}V_{i,t} \le V_{i,t} \le \mathrm{Max}V_{i,t} \tag{3}$$

where $\mathrm{Max}V_{i,t}$ and $\mathrm{Min}V_{i,t}$ are maximum and minimum storages of ith station allowed during period t respectively.

Generation power capacity bounds for each hydropower:

$$\mathrm{Min}p_{i,t} \le p_{i,t} \le \mathrm{Max}p_{i,t} \tag{4}$$

where $\mathrm{Max}p_{i,t}$ and $\mathrm{Min}p_{i,t}$ are maximum and minimum generation power capacity of ith station allowed during period t respectively.

Turbine capacity constraint:

$$\mathrm{Min}Q_{i,t} \le Q_{i,t} \le \mathrm{Max}Q_{i,t} \tag{5}$$

where $\mathrm{Max}Q_{i,t}$ and $\mathrm{Min}Q_{i,t}$ are maximum and minimum turbine capacity of ith station allowed during period t respectively.

In addition to the above constraints, it should be ensured that minimal mean power of hydropower system P can satisfy the charge demand of power grid system.

$$\sum_{i=1}^{N} p_{i,t} \ge P \tag{6}$$

Otherwise, it should be ensured that initial and end storages of ith station during the first and last periods are equal to some fixed storages, ie,

$$V_{i,1} = Vb_i\,, \quad V_{i,N} = Ve_i \tag{7}$$

where Vb_i and Ve_i are the storages of ith station during first and last periods respectively.

Particle Swarm Optimisation

Particle Swarm Optimisation (PSO) is a recently proposed algorithm by Kennedy and Eberhart (1995), motivated by social behavior of organisms such as bird flocking and fish schooling. PSO shares many similarities with evolutionary computation techniques such as genetic algorithms (GA). The system is initialised with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. PSO, as an optimisation tool, provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multi-dimensional search space. During flight, each particle adjusts its position according to its own experience, and according to the experience of a neighboring particle, making use of the best position encountered by itself and its neighbor. Thus, as in modern GAs, a PSO system combines local search methods with global search methods, attempting to balance exploration and exploitation.

PSO is developed through simulation of bird flocking in 2-dimensional space. The position of each agent is represented in X-Y plane with position (s_x , s_y), v_x (velocity along X-axis), and v_y (velocity along Y-axis). Modification of the agent position is realised by the position and velocity information.

Bird blocking optimises a certain objective function. Each agent knows its best value so far, called 'Pbest', which contains the information on position and velocities. This information is the analogy of personal experience of each agent. Moreover, each agent knows the best value so far, in the group 'Gbest' among Pbests. This information is the analogy of knowledge, how the other neighboring agents have performed. Each agent tries to modify its position by considering current positions (s_x , s_y), current velocities (v_x , v_y), the individual intelligence (Pbest), and the group intelligence (Gbest).

The following equations are utilised, in computing the position and velocities, in the X-Y plane:

$$v_i^{k+1} = \varphi_0 \,x\, v_i^K + \varphi_1 \,x\, \mathrm{rand}_1 \,x\, (\mathrm{Pbest}_i - s_i^K) + \varphi_2 \,x\, \mathrm{rand}_2 \,x\, (\mathrm{Gbest} - s_i^K) \tag{8}$$

$$s_i^{K+1} = s_i^K + v_i^{K+1} \tag{9}$$

where v_i^{k+1} is the velocity of (k + 1)th iteration of ith individual, v_i^k is the velocity of kth iteration of ith particle, φ_0 is the inertial weight, φ_1,

φ_2 are the positive constants, having values [0, 2], $rand_1$, $rand_2$ are the random numbers selected between 0 and 1, $Pbest_i$ is the best position of the ith particle, Gbest is the best position among the individual (group best) and s_i^k is the position of ith particle at kth iteration.

Two Stage PSO Algorithm for Hydroelectric Power System

From Eqn (2) to Eqn (7), the optimisation problem of a hydroelectric power system involves the complex constraints. Our experiences show that most particles in stochastic generated initial swarm are usually unfeasible for the operation problem of the hydroelectric power system considering that storage volumes of a reservoir are restrained to each other when using the storages as decision variables. Furthermore, the feasible solution will be more difficult to obtain by stochastic generation when the minimal mean power restriction is taken into account at the same time. Thus, it is very difficult to directly apply PSO to the optimisation problem of a hydroelectric power system.

A two stage particle swarm optimisation approach is presented towards this problem. In the first stage, the maximisation of minimal mean power of the hydropower system instead of maximisation of electricity generation is taken as objective in order to make the initial particle swarm collected to feasible area. The evolution computation starts from stochastic generated particle swarm until the constraint of mean power is reached. The position s_i^k and the velocity v_i^k, representing the storage and search step respectively of ith reservoir during the kth iteration, are vectors containing 12 elements. They are updated through Eqn (8) and Eqn (9). In this stage, the water balance and minimal power restriction for a single power station are dealt with by different penalty coefficients. The objective function is translated as:

$$E = \max\Big[\min\sum_{i=1}^{N}\big(p_{it} + \lambda_1(V_{i,t+1}, V_{i,t})\min((V_{i,t} - V_{i,t+1})/\Delta_t + q_{i,t}, 0) + \lambda_2\min(p_{it} - Minp_{i,t}, 0)\big)\Big] \qquad (10)$$

In the second stage, the evolution of particle swarm is continued following the objective and restriction of the original model until the termination condition is reached. In this stage, different penalty coefficients are used to water balance, minimal power of single station and minimal power of the whole system. The objective function is changed as:

$$E = \max\big[e + \lambda_3\max(e - P\Delta_t, -P\Delta_t)\big] \qquad (11)$$

$$e = \sum_{i=1}^{N}\Delta_t\big(p_{it} + \lambda_1(V_{i,t+1}, V_{i,t})\min((V_{i,t} - V_{i,t+1})/\Delta_t + q_{i,t}, 0) + \lambda_2\min(p_{it} - Minp_{i,t}, 0)\big) \qquad (12)$$

For Eqn (10) to Eqn (12), $\lambda_1(V_{i,t+1}, V_{i,t}) = ((L_{i,t+1} + L_{i,t})/2 - Z_{i,t})$, λ_2, λ_3 are penalty coefficients, e is a temporary variable, $L_{i,t}$ is the initial storage level of ith station in period t. $Z_{i,t}$ is the lower level of ith station in period. $\lambda_2 = 100$, $\lambda_3 = 10$.

Case Study

Implementation of the proposed method is demonstrated through a large scale hydroelectric power system in the Yunnan power grid, Yunnan Province, Southern China. The Yunnan Province is replete with natural water resources. It is estimated that the exploitable hydro capacity in Yunnan is nearly 100 GW, accounting for a quarter of the whole national exploitable hydro capacity, rank second in China. Most of the planned and established hydropower plants in Yunnan are located on the Jinsha river and the Lancang river. Jinsha river, the upper stream of the Yangtze River, has exploitable hydropower of more than 18 GW where 40,940 MW is within Yunnan. The Lancang mainstream in Yunnan is planned for exploiting into 14 cascade developments with a total installed capacity of about 22,590 MW. Up to 2006, the installed capacity of hydropower system is over 10,000 MW. Along with the successive commencement of a group of large hydropower projects namely the Xiaowan, Nuozhadu, Xiluodu and Xiangjiaba Hydropower Projects, Yunnan has entered a rapid development period of hydropower. The installed capacity of hydropower system in Yunnan will exceed 20,000 MW by the end of 2010 and 60,000 MW by the end of 2020. It is very important to develop the optimisation models of the large-scale hydropower system operations.

For the current and future operations of the large-scale hydropower system in Yunnan, the Yunnan power grid had launched a project of optimising the large-scale hydropower system operations since 2003 and focused on the hydropower system which consists of 17 dominated hydropower plants (Fig 1) with an installed capacity of 3,942.5 MW until 2005. These hydropower plants are distributed in the following five basins: 1) Lancangjiang river where Manwan and Dachaoshan are two of the built hydropower plants in the mainstream and the four series of Xierhe hydropower plants are located at its tributary in the Xierhe river; 2) Yilihe river, an independent river, where four series of Yilihe hydropower plants have been built in this river; 3) Huanglihe river where the Lubuge hydropower plant has been built; 4) Sayuhe river, four series of hydropower plants have been planned and the Gaoqiao reservoirs with two series have been built; 5) Nanpangjiang river where the Chaishitan reservoir has been built. The Yunnan power grid is a part of China Southern Power Grid and has an important task of transferring electric power to Guangxi Province, Guangdong Province and Vietnam. The Yunnan power grid needs to define the monthly, weekly and daily operational rules. The main operational objective is to maximise the potential energy of the system and ensure the various tasks of transferring electric power. The current study in this paper is a part of the hydrothermal power operation management system of the Yunnan Power Grid and is integrated into this system. The main objective is to establish an optimisation model using PSO for planning the long-term operation of the hydroelectric power system.

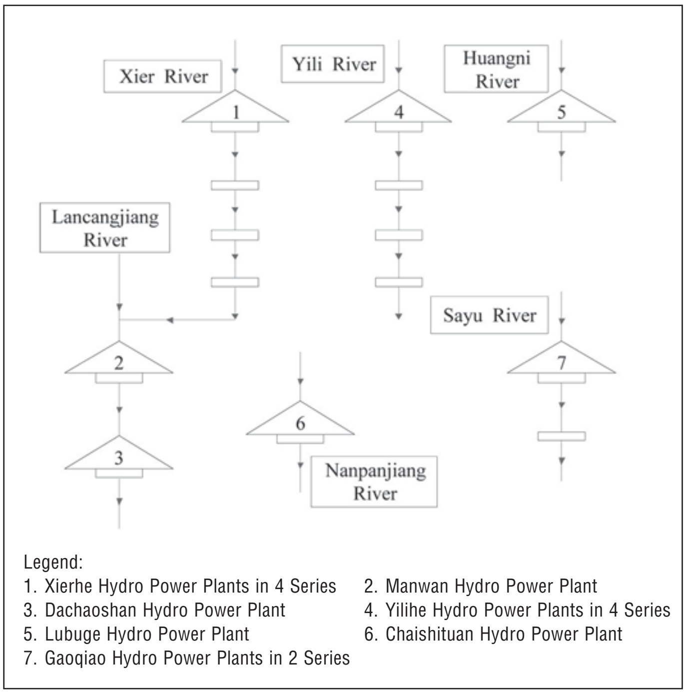

Figure 1 – Schematic Layout of the Domain Hydro Power System in Yunnan

The details of the basic characteristics of each reservoir, including total installed capacity, greatest discharge of turbines, etc, are given in Table 1. Deterministic monthly flows were used in this study. To the current knowledge, it is difficult to obtain a desirable result of long-term forecasting runoff. An alternative for dealing with the long-term flows is to randomly simulate runoff based on historical records (Wang *et al.,* 2005). Stochastic dynamic programming (SDP) (El-Awar *et al.,* 1998; Kracman *et al.,* 2006) or a hybrid of SDP is used to cope with the long-term operation of a multi-reservoir system (Huang *et al.,* 2002). Usually, SDP or their hybrid are applied to define the operational rules

Hydrpower Plant	Total Installed Capacity (MW)	Greatest Discharge of Turbines (m^3/s)	Normal Elevation (m)	Flood Control Elevation (m)	Dead Elevation (m)	Overall Hydropower Plant Efficiency
Manwan	1,250	1,960	994	987	982	8.6
Dachaoshan	1,350	2,084	899	888	882	8.8
Xierhe 1	105	57	1,974.2	1,973.5	1,972.6	7.96
Xierhe 2	50	55	1,730	-	1,721	7.96
Xierhe 3	50	57	1,610	-	1,605	7.64
Xierhe 4	50	55	1,488.9	-	1,483	7.91
Yilihe 1	16	29	2,227	2,225	2,180	7.59
Yilihe 2	17.5	29	2,100	-	2,096	8.03
Yilihe 3	144	29	2,018	-	2,016	7.78
Yilihe 4	144	29	1,383	-	1,377	7.74
Lubuge	600	214	1,130	1,110	1,105	8.4
Gaoqiao 1	16	20	1,985	1,983	1,945	8
Gaoqiao 2	90	20	1,814	-	1,810	8
Chaishitan	60	111	1,640	1,635	1,605	8.5

Table 1 – Basic Characteristics of the Hydroelectric Power System

Month	Manwan	Dachaoshan	Lubuge	Yilihe	Xierhe	Gaoqiao	Chaishitan
1	437.0	54.0	46.5	5.8	3.4	3.5	11.3
2	384.0	37.4	38.7	5.0	0.5	2.8	8.5
3	418.0	24.5	31.8	4.1	-2.8	2.3	5.2
4	606.0	15.3	28.0	3.1	-4.5	1.8	4.3
5	871.0	22.4	54.8	4.0	-2.5	2.3	10.4
6	1,540.0	61.6	232	16.6	18.5	8.7	63.7
7	2,400.0	177.2	370	33.7	54.2	25.4	93.4
8	2,560.0	280.3	381	39.4	69.2	25.7	108.0
9	2,280.0	212.6	256	30.4	66.4	20.5	74.2
10	1,503.0	176.7	174	20.1	52.2	16.3	47.0
11	879.0	125.2	96.7	11.5	17.1	7.4	24.2
12	556.0	75.4	61.1	7.4	9.0	4.5	14.7

Table 2 – 50% Level Inflows of Each Hydroelectric Power Plant (m^3/s)

of reservoirs and are seldom applied to the practical operation planning because of the complexity of algorithms and uncertainty of optimal solutions. For practical operation planning, similar historical records or a series of flows corresponding to some frequency are used as inflows and some of simple and effective optimisation techniques are picked up. In this paper, monthly flows at 50% frequency which shown in Table 2 are used as an example for demonstrating the algorithms.

The hydrothermal power operation management system of the Yunnan Power Grid was developed with Java 2 platform Enterprise Edition (J2EE) and Eclipse3.2 as the development tool. The proposed algorithm in this paper was also developed by Java. All computational results are gained under the condition of PC-Intel Xeon 5140@2.33 GHz. Table 3 gives the maximum and minimum operating generation capacity of each hydroelectric power plant for every month. The two scenarios of total generation capacity of the multi-resevoir power system were tested, respectively 1,250 MW and 1,300 MW. In this study, the parameters of PSO are $\varphi_0 = 0.4$, $\varphi_1 = 2$, $\varphi_2 = 2$, $r = 0.1$.

Fig 2 lists the optimal elevation procedure of each reservoir constrained by the 12,500 MW of the total generation capacity of the multi-resevoir power system. Accordingly, Table 4 displays the optimal results of the average generation capacity of each hydropower plant and Fig 3 shows the optimal result of total generation capacity of the multi-resevoir power system. Similarly, Fig 4, Table 5 and Fig 5 show the optimal results constrained by the 13,000 MW of the total generation capacity of the multi-resevoir power system. These operation results are described as the following.

1. For the hydropower plants with regulation capacity such as the series of the Xierhe, the series of the Yilihe, the series of the Gaoqiao and the Chaishitian, they have the tendency of enhancing the average capacity during the drought season from January to May and uplift their elevation from the lowest step by step when elevations decrease in June or July.
2. For the Manwan and Dachaoshan hydropower plants with a part of regulation capacity and a great installed capacity, they will maintain a high elevation in order to increase the generation power except for flood seasons from June to September.
3. Results 1 and 2 above are reasonable, which show that applying PSO to the long-term operation of a hydroelectric power system is feasible.

For demonstrating the effectiveness of the proposed algorithm, we also compared the convergence speed both with and without using initial solutions. Fig 6 and Fig 7 show the evaluation of convergence rate for two stage PSO with different initial conditions under 12,500 MW and 13,000 MW of the total generation capacity of the multi-resevoir power system respectively. Table 6 demonstrates the comparison of performance with different initial conditions. Generally, it is difficult to give a feasible solution if we directly apply PSO to cope with the problem in this paper. Conversely, a two stage PSO was able to provide feasible solutions once we set a suitable number of population (for this paper, more than 200). Two stage PSO relaxed the difficult constraint of the total generation capacity of the multi-resevoir power system, and thus spanned its search. Figs 6 and 7 as well as Table 6 indicate that giving an initial optimal solution trajectory can speed up the convergence through decreasing the number of population and improve the solution. Table 6 also displays that the optimal results have an increasing tendency with the number of population when the initial optimal solution trajectory was given. Furthermore, the optimal results of two stage PSO with a suitable number of population (100) and an initial optimal solution trajectory can give similar results

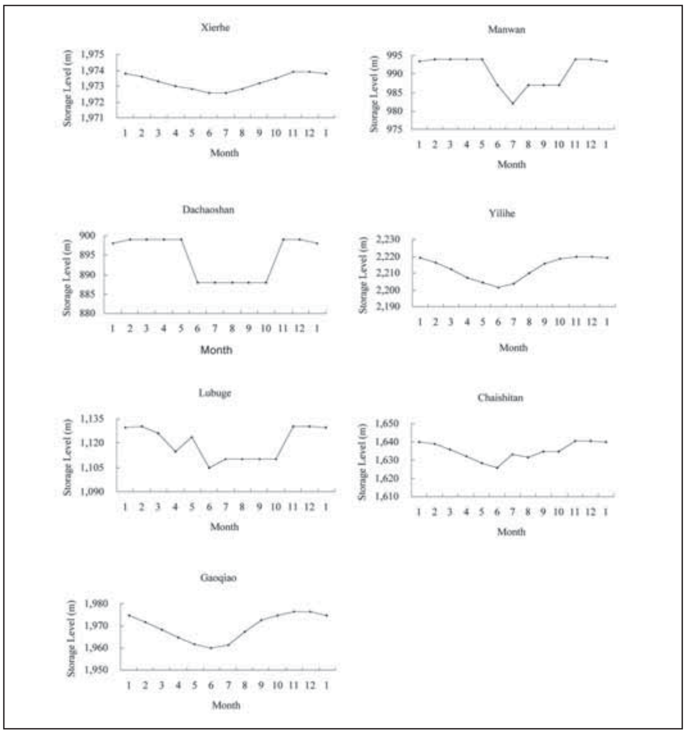

Figure 2 – Level Procedure of Each Reservoir Constrained by 12,500 MW of Average Capacity of the System

Month	Manwan		Dachaoshan		Lubuge		Yilihe Series		Xierhe Series		Gaoqiao Series		Chaishitan Series	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
1	940	150	1,000	150	450	50	280	42	192	21	106	30	60	10
2	940	150	1,000	150	450	50	280	42	192	21	106	30	60	10
3	940	150	1,000	150	450	50	280	42	192	21	106	30	60	10
4	940	150	1,000	150	450	50	280	42	192	21	106	30	60	10
5	940	150	1,000	150	450	50	280	42	192	21	106	30	60	10
6	1250	150	1,350	150	600	50	220	42	255	21	68	30	60	10
7	1250	150	1,350	150	600	50	220	42	255	21	68	30	60	10
8	1250	150	1,350	150	600	50	220	42	255	21	68	30	60	10
9	1250	150	1,350	150	600	50	220	42	255	21	68	30	60	10
10	1250	150	1,350	150	600	50	220	42	255	21	68	30	60	10
11	940	150	1,000	150	450	50	280	42	192	21	106	30	40	10
12	940	150	1,000	150	450	50	280	42	192	21	106	30	40	10

Table 3 – Maximum and Minimum Operating Generation Capacity of Each Hydroelectric Power Plant (MW)

Month	Manwan	Dachaoshan	Lubuge	Yilihe Series	Xierhe Series	Gaoqiao Series	Chaishitan Series	System
1	341.01	352.67	138.64	227.9	98.23	81.57	10	1,250.02
2	304.08	314.71	136.08	274.73	129.13	76.03	15.23	1,249.99
3	330.72	330.04	134.56	258.25	117.07	67.99	11.41	1,250.04
4	477.12	459.04	50	126.82	76.77	50.71	10.04	1,250.5
5	697.95	703.46	214.2	120.11	77.52	30.97	10	1,854.21
6	1,087.99	974.28	574.89	115.5	84.98	30.18	24.42	2,892.24
7	1,125	1,183.95	572.19	121.07	153.42	37.43	60	3,253.06
8	1,125	1,164.33	572.19	127.78	153.81	47.27	59.97	3,250.35
9	1,125	1,187.03	565	128.9	154.48	59.02	47.4	3,266.83
10	1,070.74	983.15	415.12	124.8	64.27	43.32	17.5	2,718.9
11	686.56	724.22	284.28	130.3	84.88	46.71	16.67	1,973.62
12	440.81	473.71	182.97	131.67	83.12	52.42	11.31	1,376.01

Table 4 – The Optimal Results of the Average Capacity of Each Hydropower Plant Constrained with 1,250 MW of the System Capacity (MW)

Month	Manwan	Dachaoshan	Lubuge	Yilihe Series	Xierhe Series	Gaoqiao Series	Chaishitan Series	System
1	341.01	352.67	138.64	278.36	101.04	79.12	10.05	1,300.89
2	304.08	314.71	138.86	279.96	146.76	90.43	25.22	1,300.02
3	330.72	330.04	115.16	277.73	161.53	68.31	16.52	1,300.01
4	477.13	459.04	77.23	178.57	54.32	43.87	10.1	1,300.26
5	697.95	703.46	205.41	103.26	27.86	31.52	10.04	1,779.5
6	1,087.99	974.28	574.89	96.86	84.98	30.79	10.01	2,859.8
7	1,125	1,183.95	572.19	99.61	153.52	32.45	52.79	3,219.51
8	1,125	1,164.33	572.19	118.35	153.23	39.33	59.94	3,232.37
9	1,125	1,187.03	565	112.23	154.97	39.34	47.4	3,230.97
10	1,070.74	983.15	415.12	100.84	78.64	49.41	17.62	2,715.52
11	686.56	724.22	284.28	107.56	78.16	54.38	16.53	1,951.69
12	440.81	473.71	182.97	108.83	75.37	61.04	11.31	1,354.04

Table 5 – The Optimal Results of the Average Capacity of Each Hydropower Plant Constrained with 1,300 MW of the System Capacity (MW)

Total Generation Capacity of the System (MW)	PSO (Number of Population)								POA	
	20		40		100		200			
	With Initial Solution						Without Initial Solution			
	Generation Power (10^8 kWh)	Time (s)	Generation Power (10^8 kWh)	Time (s)	Generation Power (10^8 kWh)	Time (s)	Generation Power (10^8 kWh)	Time (s)	Generation Power (10^8 kWh)	Time (s)
1,250	187.15	26	187.18	36	187.21	61	187.06	158	187.21	92
1,300	186.82	30	186.85	52	186.87	98	186.20	215	186.90	135

Table 6 – Comparison of Performance with Different Initial Conditions

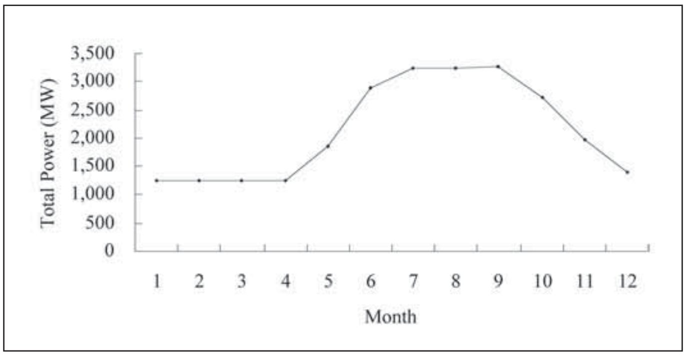

Figure 3 – Total Generation Capacity of System Constrained by 12,500 MW of Average Capacity of the System

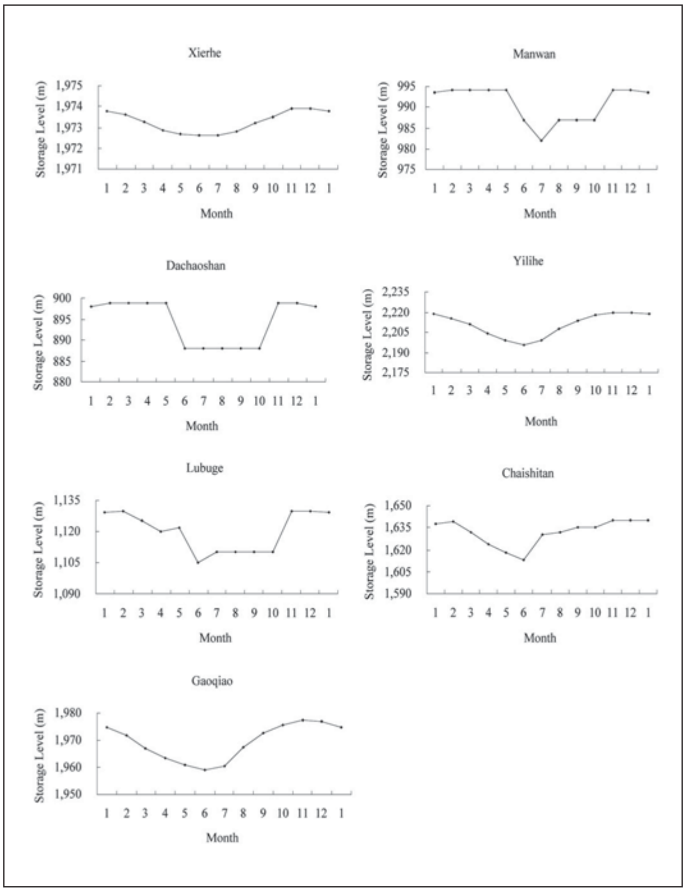

Figure 4 – Level Procedure of Each Reservoir Constrained by 13,000 MW of Average Capacity of the System

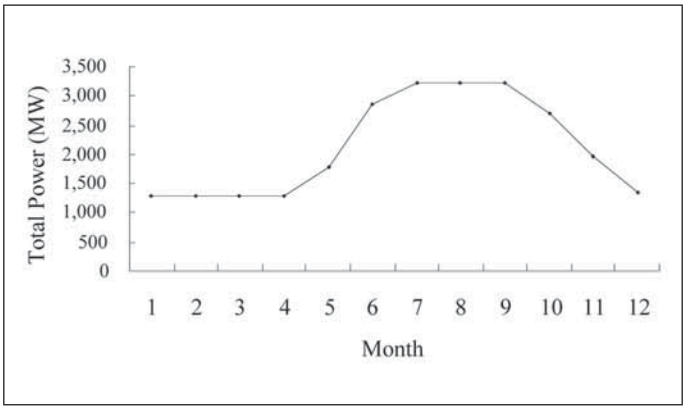

Figure 5 – Total Generation Capacity of System Constrained by 13,000 MW of Average Capacity of the System

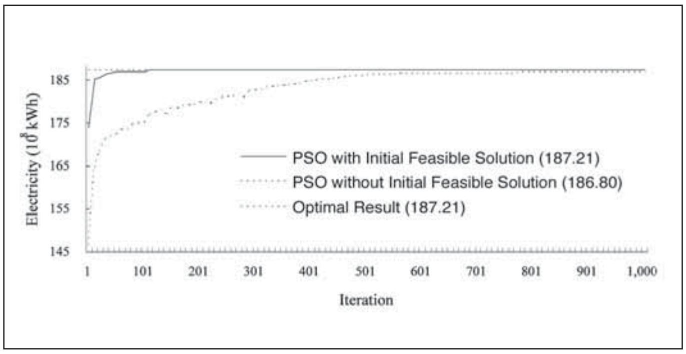

Figure 6 – Convergence for Two Stage PSO with Different Initial Conditions under 12,500 MW of Average Capacity of the System

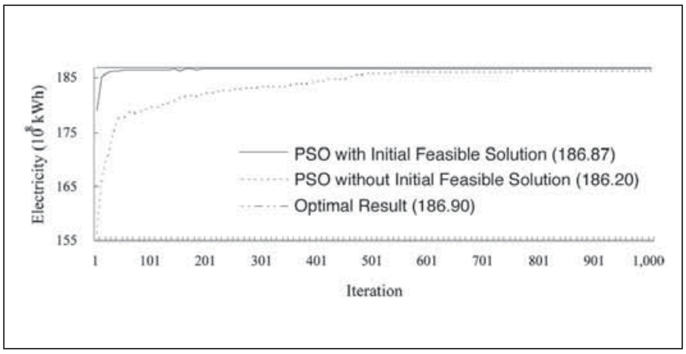

Figure 7 – Convergence for Two Stage PSO with Different Initial Conditions under 13,000 MW of Average Capacity of the System

with conventional progressive optimality algorithm (POA) but at a shorter time. These results demonstrate that the two stage PSO can provide a reasonable and efficient solution.

Conclusion

In the present study, a new and efficient technique employing a two stage PSO is presented to deal with the optimal long-term operation of a hydroelectric power system. Usually, most particles in stochastic generated initial swarm are unfeasible for the operation problem of the hydroelectric power system because of complex constraints and hydraulic relationships among multi-reservoir. It is very difficult to directly apply PSO to the optimisation problem of a hydroelectric power system. PSO must be modified for this application.

The proposed method has been implemented in a hydrothermal power operation management system of the Yunnan Power Grid, China and integrated into the system. Case study results show that two stage PSO can give reasonable and efficient solutions and is a good alternative of traditional DP and NLP techniques.

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