Development of Multi-Objective Operation Rule Curve for Hydropower Reservoir System Using Reservoir System Simulation and Constraint Optimization GA-KS, Case Study: Hydropower Reservoir System in Ca River Basin

Le Xuan Cau

***Abstract*—**Objective of the present research is the development of optimal daily rule curve for multi-purpose hydropower reservoir system. A daily rule curve consists of upper rule curve and lower rule curve. At a given time of year and current reservoir water level, an operator determines outflow discharge from reservoir by using rule curve. Multi-purpose hydropower reservoir system needs the daily rule curve to support operating effectively in both short term and long term. The rule curve is a useful tool to support the daily operation of hydropower reservoir system. The rule curve for multi-purpose hydropower reservoir system constructed for daily reservoir operation to achieve the objectives such as: the largest total electricity production, minimal spill water, the smallest shortage of water supply water level of reservoir at the end of the flood season, a higher water level at the end of the dry season than the dead water level. The article presents a method of optimal rule curve construction for hydropower reservoirs. The optimal rule curve for the hydropower system is determined by setting the objective function for reservoir operation and construction of reservoir operation rule curve by using hydropower reservoir system simulation, global optimization method (Genetic Algorithm), constraint optimization method (Kreisselmeier-Steinhauser function KS). Optimal daily rule curves have been built based on monthly rule curves. The optimal daily rule curves is determined through upper rule curve coefficient α_{upper} ($0 \le \alpha_{upper} \le 1$) and lower rule curve coefficient α_{lower} ($0 \le \alpha_{lower} \le 1$) given monthly rule curves. The advantages of optimal daily rule curves are proved by comparing operating results according to existing monthly rule curves and to optimal daily rule curves based on calibration data sets and validation data. A program for development of optimal daily rule curve for multi-purpose hydropower reservoir system is built. The program consists of hydropower reservoir system routing module, hydropower reservoir system operation module, and global constraint optimization module. There are three hydropower reservoirs on Ca River, Vietnam (The BanVe reservoir, KheBo reservoir, BanMong reservoir). Applying the program, the research has developed an optimal daily rule curve for multi-purpose hydropower reservoir system on Ca River by using daily inflow data in 41-year period. Operating according to the obtained daily rule curve for multi-purpose hydropower reservoir system will be at best goals. The research has a new contribution: The research represents a method to build a rule curve for multi-purpose hydropower reservoir system by combining hydropower reservoir system simulation and global constraint optimization.

L. X. Cau is with the Institute of Meteorology, Hydrology and Environment,23/62 Nguyen Chi Thanh Street, Dong Da District, Hanoi, Vietnam (phone: +8498-337-4341; fax: +84303-555-5555; e-mail: lexuancau@ gmail.com).

***Keywords*—**Multi-objective operation rule curve for hydropower reservoir system, hydropower reservoir system simulation, global constraint optimization GA-KS, rule curve for hydropower reservoir system in Ca River.

I. INTRODUCTION

HYDROPOWER reservoir system is operating such that available reservoir capacity is used in the most effective way [1], [3], [8]. A reservoir operation at any time of year is one of three operation type as following:

a) Normal operation
b) Operation for normal flood control
c) Emergency operation for flood control

The object of operation for normal flood control is decreasing the damage at lower zone while guaranteed damp security. The object of emergency operation for flood control is that damp security must be guaranteed.

Rule curve for reservoir system [1] is system of curves that represent the relationship between outflow from a reservoir at any time of year and the reservoir state (current reservoir capacity and inflow to reservoir). Optimal multi-objective rule curve for reservoir system is determined such that the reservoir operation according to optimal rule curve will maximize the given objectives while satisfying all constraints.

Rule curve (RC) for reservoir system is drawn such that reservoir water level is on a vertical axis and time of year is on a horizontal axis

For a single reservoir, relationship between reservoir release (outflow) Q_{out}, reservoir water level Z_R, and inflow to reservoir Q_{in} is expressed as follows:

$$Q_{out}(t)= f(t, Z_R(t), Q_{in}(t)) \quad (1)$$

Where: Q_{out} (t): outflow at t; t: time; Z_R: reservoir water level at t, Q_{in}: inflow to reservoir

For reservoir system, outflow from reservoir Q_{out} is determined based on system state and expressed as following:

$$Q_{out}= f(S_{r,1}(t), S_{r,2}(t),\ldots, S_{r,n}(t)) \quad (2)$$

where $S_{r,1}(t)$, $S_{r,2}(t)$, $S_{r,n}(t)$: state of reservoirs 1, 2,…, n at t

Relationship (2) is established through determining (1) for each reservoir using reservoir system operating simulation and multi-objective multi-constraint optimization.

Operation for normal flood control [2] is based on fuzzy system:

$$Q_{out} = \alpha * Q_{in} \quad (3)$$

Coefficient α depends on reservoir water level and inflow and determined by fuzzy relationship:

$$\alpha = f(Z_r, Q_{in}) \quad (4)$$

where Z_r, Q_{in} are represented in the form of fuzzy variable.

USACE standard emergency rule curve is used for the emergency flood control (United State Army Corps of Engineers) [3], [4]

A method of construction of optimal multi-objective daily rule curve for the hydropower reservoir system and case study on hydropower reservoir system in Ca River are presented in the next section II, III.

II. Development of Optimal Multi-objective Daily Rule Curve for Hydropower Reservoir System

A. Method of Construction of Optimal Multi-objective Daily Rule Curves for Hydropower Reservoir System

Optimal multi-objective daily rule curves for hydropower reservoir system is built through optimal upper curve and lower curve coefficients α_{upper} *($0 \le \alpha_{upper} \le 1$, α_{lower} ($0 \le \alpha_{lower} \le 1$)* and monthly rule curves. Optimal coefficients α_{upper},α_{lower} is determined by multi-objective optimization GA-KS

Coordinate of daily rule curves is computed based on α_{upper} and α_{lower}:

Suppose Z_{upper}, Z_{lower} are coordinates of monthly upper rule curve and monthly lower rule curve, respectively, then coordinate of *daily upper rule curve* according to α_{upper} is computed as formulae:

$$Z_{\propto\_upper} = Z_{upper} - \propto_{upper} * \left(\frac{Z_{upper} - Z_{lower}}{2}\right) \quad (5)$$

Coordinate of daily lower rule curve according to α_{lower} is computed as formulae:

$$Z_{\propto\_lower} = Z_{lower} + \propto_{lower} * \left(\frac{Z_{upper} - Z_{lower}}{2}\right) \quad (6)$$

Daily upper rule curve and daily lower rule curve can be used as the following:

Outflow from reservoir at any time of year is determined by the reservoir water level Z and the relative position comparing to the rule curves.

Suppose that Z_{normal} is a normal water level of reservoir. Z_{max}, Z_{min} are the maximum and minimum water level of reservoir, respectively. Z is the water level of reservoir at operation time, $N_{guaranteed}$ is guaranteed hydroelectric power, N_{max} is maximum hydroelectric power, and N is the operating hydroelectric power. N is determined as the following:

1, If $Z \le Z_{\alpha\_upper}$ and $Z \ge Z_{\alpha\_lower}$ then

$$N = N_{guaranteed} \quad (7)$$

2, If $Z \ge Z_{\alpha\_upper}$ and $Z \le Z_{normal}$ then

$$N_{guaranteed} + \frac{(Z - Z_{\propto\_upper})}{(Z_{normal} - Z_{\propto\_upper})}\left(N_{max} - N_{guaranteed}\right) \quad (8)$$

3, If $Z \le Z_{\alpha\_lower}$ and $Z \ge Z_{min}$ then

$$N = N_{guaranteed} - \frac{(Z_{\propto\_lower} - Z)}{(Z_{\propto\_lower} - Z_{min})} N_{guaranteed} \quad (9)$$

4, If $Z \ge Z_{normal}$ then

$$N = N_{max} \quad (10)$$

Reservoir capacity W can be substituted instead of reservoir water level Z in (7)-(9). This is a more complex computation, but it will give the better result.

Daily upper rule curve and daily lower rule curve are built by simulating the hydropower reservoir system operation. The operation is carrying out such that the hydroelectric power output of reservoir system is maximized, the reservoir capacity at the end of flood season is maximized, and the reservoir water level at the end of dry season is above the death water level and constraints at control points are satisfied. A tool for determining optimal daily rule curve for hydropower reservoir system is developed by Visual Basic .NET. The tool consists of the modules: Hydropower reservoir routing, river routing module, system control module and multi-objective optimization module (GA-KS). Genetic algorithm has been applied to multi-objective optimization of water use, [5]-[9].

B. Application of Genetic Algorithm (GA) and Kreisselmeier-Steinhauser Function (KS) to build an Optimal Multi-objective Daily Rule Curves for Hydropower Reservoir System

Multi-objective optimization can be considered as vector optimization. Suppose that a vector consists of p of objective $Z_j(X)$, j=1, 2, .., p, then objective function can be expressed in the form:

$$\textit{maximize}\ (Z_1(X), Z_2(X), \dots, Z_p(X)), \quad (11)$$

$$\textit{Subject to}\ \ G_i(X) < 0,\ i = 1, 2, \dots, K$$

Where, X is an input vector

Constraint optimization problem is solved by using GA [10], [11] and Kreisselmeier-Steinhauser function(KS). The main point when applying GA for constraint optimisation is how to deal with the constraints.

Using KS function and the agglomeration features of KS function, the all constraints of optimization problems are agglomerated to only one constraint whose precision is controlled by one parameter, then GA is used to solve the optimal problem with only one objective function after the compression of constraints.

The multi-constraint optimization problem can be written as:

$$\text{Min } y = f(X), \quad (12)$$

Subject to $g_j(X) \le 0$, $(j = 1, \cdots, m)$

where, f (x), g (X) are real valued functions defined on E_n, and $X \in E_n$ is an n-dimensional real vector with components x_1, x_2, … , x_n that satisfy the restrictions and meanwhile minimize the objection, the set $F \subset E_n$ defines the feasible region. Let $g_j(X)$ (j = 1, 2, …, m) is real function set in n-dimension Euclidean space, where $X \in E_n$. In exponential space, the maximum quasi-differentiable envelop of the $g_j(X)$ is defined as follows:

$$KS(\rho, X) = \frac{1}{\rho}\ln[\sum_{j=1}^{m} e^{\rho * g_j(X)}] \quad (13)$$

Where, ρ >0, ρ is a given control parameter.

A function sgn(x) can be defined as follows:

$$sgn(x) = \begin{cases} 1 \ if \ x > 0 \\ 0 \ if \ x < 0 \end{cases}$$

A simple penalty function can be constructed:

$$\varphi(X) = f(X) + M \times sgn(KS(\rho, X)) \quad (14)$$

Where, M is an enough big positive number. The problem (11) can be transformed to an unconstrained problem: Min φ (X). The solution X* of min φ (X) is the minimal solution or approximate minimal solution. If we get $X* \in M$, it must be the minimal solution of the multi-constrained problem

III. CASE STUDY: BUILDING OPTIMAL MULTI-OBJECTIVE DAILY RULE CURVES FOR HYDROPOWER SYSTEM

A. Ca River Basin and Hydropower Reservoir Systems: BanVe, KheBo, BanMong

Ca River basin is one of the large basins in the north Centre of Vietnam; it is an international river basin with 531 km of length and occupying the area of 27200 km^2 in which the area in Vietnam territory is 17730 km^2, holding 65.2% of the total basin area. In this part, the population is 3358000 with eight ethnic groups. Originating from Mt. MuongKhut and MuongLap (1800 ÷ 2000 m), it runs northwest – southeast through three provinces of ThanhHoa, NgheAn and HaTinh before flowing out into the East Sea via Cua Hoi river mouth. Ca river basin is on the northern part of Central Vietnam, with latitude ranging from 18°15' to 20°10'30" North and longitude ranging from 103°45'20" to 105°15'20" East. Every year, the basin receives average precipitation of 1100 ÷ 2500 mm. In the large rainfall centers such as upstream of Hieu, La and Giang Rivers, average annual rainfall can reach to 2000 ÷ 2400 mm. In the Ca River basin, there are three major hydropower reservoirs being operated (Fig. 1): Ban Mong reservoir on the Hieu River, BanVe reservoir and KheBo reservoir on the Ca River. They are multi-objective reservoirs (hydroelectric power output, flood control and water supply). The operation of these reservoirs, which have a total storage capacity of 2.8 x 10^9 m^3, an installed power generation capacity of 485 MW (excluding Song Sao) has to meet flood control with 411 x 10^6 m^3 storage available, hydropower generation, water supply for irrigating 33487 hectares, industrial, domestic and environmental demand. Operation rules are built for single reservoirs.

TABLE I

THREE MAJOR HYDROPOWER RESERVOIRS IN CA RIVER BASIN

Reservoir name	BanMong	BanVe	KheBo
River name	Hieu	Ca	Ca
Basin Area F_{basin} (km^2)	2800	8700	14300
Normal Water Level(m)	76.4	200	65
Death water level WL: (m)	71	177.5	63
Reinforced water level(m)	78.08	202.24	
Average Capacity V_{avg} (Mil. m^3)	235.50	1834.6	97.8
Death Capacity V_{death} (Mil. m^3)	121.74	451.6	80.6
Effective Capacity $V_{effective}$ (Mil. m^3)	113.76	1383	17.2
V_{pl} (Mil. m^3)	-	300.00	-
Design Electric Power $N_{guaranteed}$(MW)	42	320	100

B. Multi-objective Operation of Hydropower Reservoir System in Ca River Basin

Method of building optimal multi-objective daily rule curves for hydropower reservoir system in Ca River Basin is implemented through 5 steps:

- Inflow data and characteristics of the reservoirs and monthly rule curves for the reservoirs are collected
- Setting objectives and constraints for operating reservoir system
- Set up hydropower operating simulation system model and integrate the model with global constraint optimization module GA-KS
- Simulation calculation is carrying out under the design monthly rule curve and under optimal rule curve
- Multi-criteria analysis of obtained solutions is carried out to find the best solution

Input data that are used to build optimal multi-objective rule curve for reservoir system in Ca River Basin includes:

1. Hydraulic scheme of Ca River (The three reservoirs: BanVe, KheBo, BanMong)
2. Characteristics of the reservoirs and monthly rule curve for the reservoirs
3. Daily inflow (m^3/s) to the reservoirs [12], daily lateral flow (m^3/s) from 1960 and 2003. The BanVe Reservoir inflow hydrograph from 1964-2003 is shown in Fig. 1. The dataset is divided into two sub datasets: sub dataset 1 from 1960 to 1994 is used to calibrate (search optimal parameters), subdataset2 from 1995 to 2003 is used to validate (reservoir operation independent test).
4. Environment flows at 03 control points (three reservoir downstream sites) and at two hydrological stations in reservoir downstream: Dua Station, YenThuong Station (constraints for outflows from reservoirs). Objectives building optimal rule curves need to reach:

1. Hydroelectric power output is maximized;
2. Spill water volume is minimized;
3. Reservoir water level at the end of flood season Z_3 is maximized (target is normal water level, reservoir storage at the end of flood season is the largest for conversion purpose);

4. Reservoir water level at the end of dry season Z_2 is above the death water level Z_{death} (to prevent extreme drought events that dry season may be expanded)
5. Water Shortage Index SI (15) and frequency of water deficit SFreq (16) is minimized;

Shortage index SI is computed as the following formulae:

$$SI = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{Sh_i}{D_i}\right)^2 \quad (15)$$

Where, N: Number of time interval, Sh_i: Water deficit for i^{th} time interval, D_i: Water demand for i^{th} time interval.

Shortage frequency SFreq is computed by using the following formulae:

$$SFreq = \frac{n}{N} \quad (16)$$

Where, n: number of water shortage day, N: Total number of computation day

Some constraints must be satisfied: reservoir release must be larger than environment flow at control points and water level at pump control point is larger than 1.12 m.

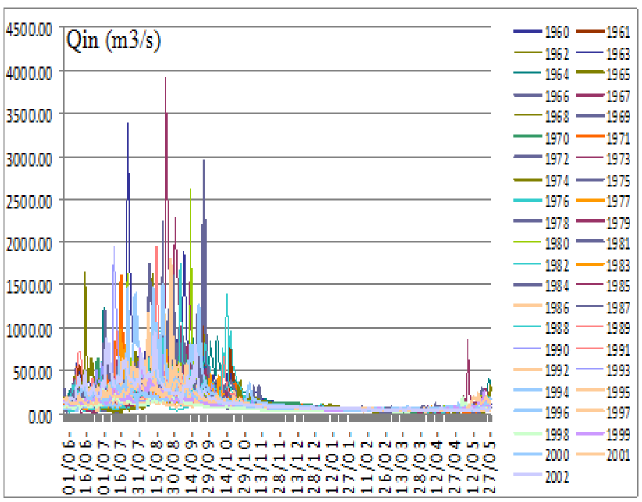

Fig. 1 Inflow hydrograph of BanVe Reservoir from 1964-2003

C. Optimal Multi-objective Daily Rule Curves for Hydropower Reservoir System in Ca River

Hydraulic computational scheme of Ca River have 18 computation nodes: three inflow input nodes, two nodes flow between zones, three reservoir input nodes and three reservoir outflow nodes and five control nodes, the remaining nodes are the computation nodes in the river flow (Fig. 2).

Daily inflow data in dataset (data from 1960 to 1994) are used to build optimal multi-objective daily rule curves. The data set is divided into two sub data sets: sub dataset 1 including data from 1960 to 1994 is used for finding optimal parameters, sub dataset 2 including data from 1995-2003 is used for reservoir operation independent test.

A simulation calculation is carrying out for four cases:

1. Operating reservoir system under current regulations (Operating under the design monthly rule curve)
2. Operating reservoir system in changing value of the α_{upper}, α_{lower} from 0 to 1 with step 0.1
3. Determining optimal α_{upper} , α_{lower} by using system simulation and GA-KS
4. Operating system using optimal α_{upper}, α_{lower}. The obtained results are compared with the results for case 1

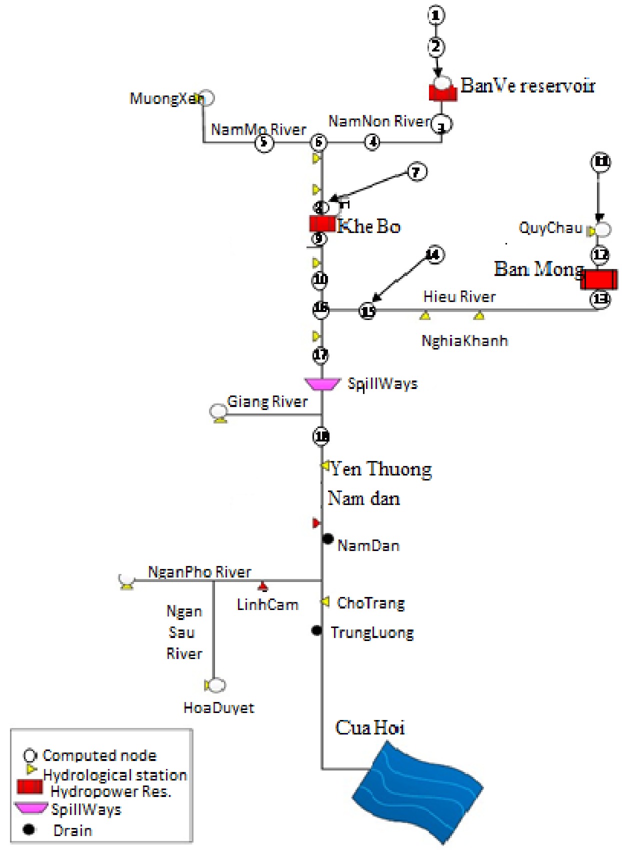

Fig.2 Computational scheme for the hydropower reservoir system in Ca River

For BanVe Reservoir, an optimal multi-objective daily upper rule curve for hydropower reservoir system operation is obtained with optimal parameter α_{upper}=0.0657, the daily upper rule curve lies near to the monthly upper rule curve. An optimal multi-objective daily lower rule curve for hydropower reservoir system operation is obtained with the optimal parameter α_{lower} =0.9853, the daily lower rule curve lies at distance about 1/2 (from bottom) between the monthly lower rule curve and the monthly upper rule curve (Fig. 2)

For BanMong Reservoir, an optimal multi-objective daily upper rule curve for hydropower reservoir system is obtained with optimal parameter α_{upper}= 0.0483, the daily upper rule curve lies near to the monthly upper rule curve. An optimal multi-objective daily lower rule curve for hydropower reservoir system are obtained with optimal parameter α_{lower} = 0.4625, the daily lower rule curve lies at distance about ¼ (from bottom) between the monthly lower rule curve and the monthly upper rule curve (Fig. 3)

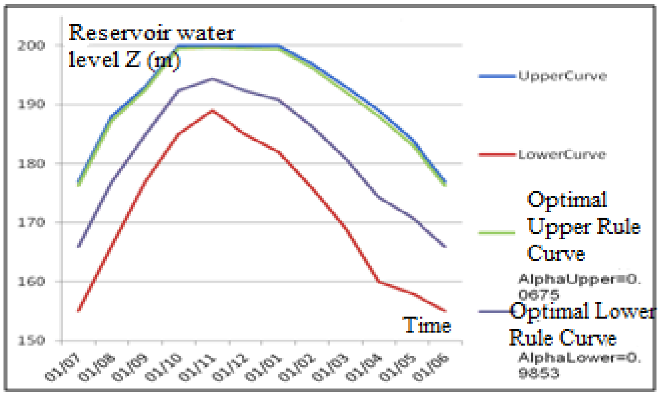

Fig.3 Optimal daily rule curve for BanVe Reservoir operating hydropower reservoir system in Ca River

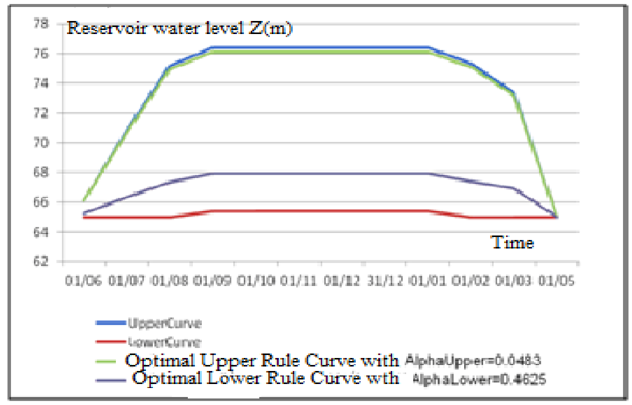

Fig. 4 Optimal daily rule curve for BanMong Reservoir operating hydropower reservoir system in Ca River

TABLEII

RESULTS OF DETERMINING OPTIMAL MULTI-OBJECTIVE DAILY RULE CURVES FOR HYDROPOWER RESERVOIR SYSTEM IN CA RIVER BASIN

No	Reservoir Name	URC coefficient α_{upper}	LRC coefficient α_{lower}	Yearly power output N (Bill. Kwh)	Spill flow $W_{spill}(m^3)$	Reservoir WL at the end of dry seasonZ2 (m)	Reservoir WL at the end of flood season Z3 (m)	Shortage frequency (%)	Shortage Index
1	Ban Ve	0.0675	0.9853	1.05	2.08E+08	163.50	184.20	0	0
2	Khe Bo	0.7062	0.2138	0.402	6.48E+08	63	63.10	2.3	1.17
3	Ban Mong	0.0483	0.4625	0.142	6.14E+08	65.01	75.66	3.59	0.61

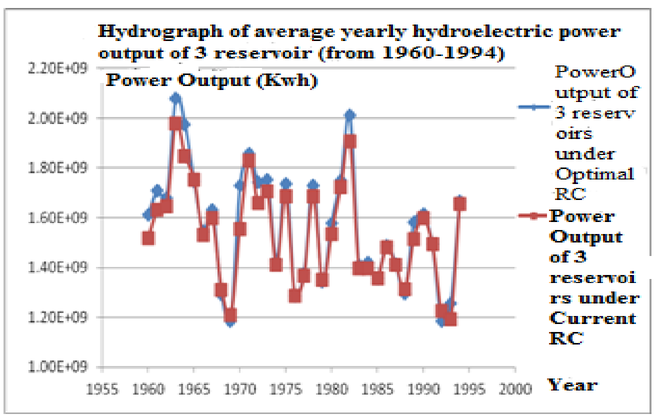

Fig. 5 Hydrograph of average yearly hydroelectric power output of 3 reservoir (from 1960-1994) (operation under current and optimal RC)

Fig. 5 shows that the average yearly hydroelectric power output of three reservoirs (from 1960-1994) operating under current RC is larger than under optimal RC. Fig. 6 shows that for independent test, the average yearly hydroelectric power reservoirs (from 1995-2003) operating under current RC is larger than under optimal RC. Effective of using optimal multi-objective daily rule curves for hydropower reservoir system in Ca River Basin is clear in Table III.

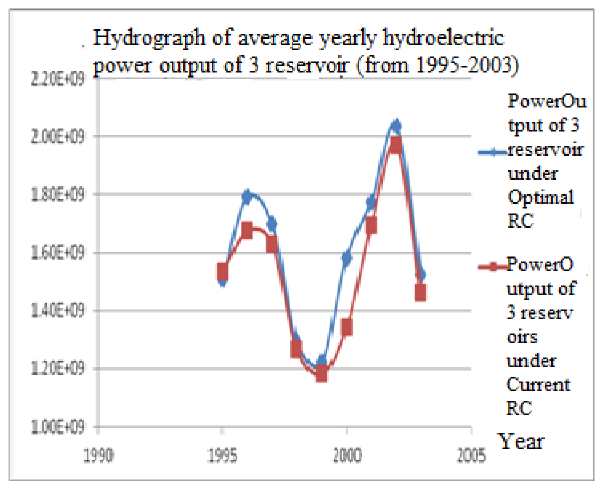

Fig. 6 Hydrograph of average yearly hydroelectric power output of 3 reservoir (from 1995-2003) (independent test operation under current and optimal RC)

Multi-criteria analysis is carried out, and the best solutions can be found. For example, Fig. 7, 8, 9 show that there exists a number of pareto optimal solutions for BanVe reservoir.

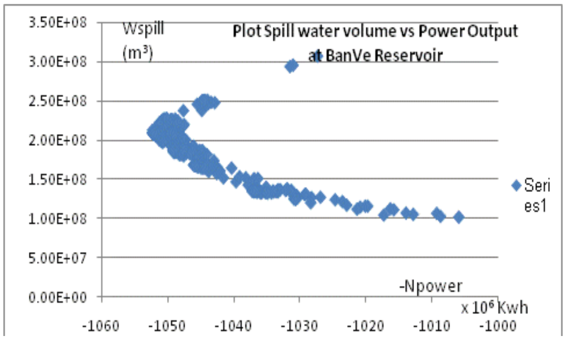

Fig. 7 Plotting Spill water volume vs Power Output at BanVe Reservoir

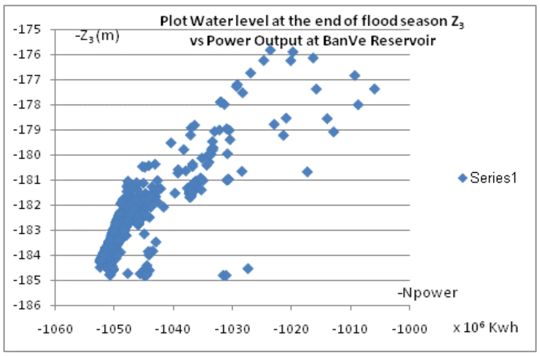

Fig. 8 Plotting water level at the end of flood season Z_3 vs power output at BanVe Reservoir

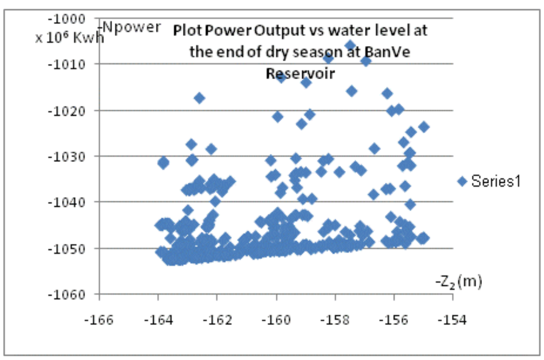

Fig. 9 Plotting power output vs water level at the end of dry season at BanVe Reservoir

TABLEIII

EFFECTIVE OF USING OPTIMAL MULTI-OBJECTIVE DAILY RULE CURVES FOR HYDROPOWER RESERVOIR SYSTEM IN CA RIVER BASIN

No	Objects	properties	All data	For calibration dataset	For validation dataset
1	Upper , lower daily rule curve coefficients	$\alpha_{upper}1$ (Res. No1)	0	0.0675	0.0675
		$\alpha_{lower}1$ (Res. No1)	0	0.9854	0.9854
		$\alpha_{upper}2$ (Res. No2)	0	0.7063	0.7063
		$\alpha_{lower}2$ (Res. No2)	0	0.2139	0.2139
		$\alpha_{upper}3$ (Res. No3)	0	0.0483	0.0483
		$\alpha_{lower}3$ (Res. No3)	0	0.4625	0.4625
2	All three reservoirs	NpowerSum (Kwh)	1.56 x10^9	1.59x10^9	1.56 x10^9
3	Ban Ve Reservoir	Z2(m)	155.20	163.50	166.74
		NpowerAverage(x10^6 Kwh)	1023.62	1052.16	1028.83
		Wspill(m^3)	2.61x10^8	2.08 x10^8	7.43 x10^8
		Z3(m)	182.09	184.21	185.16
4	Khe Bo Reservoir	Z2(m)	63.00	63.00	63.03
		NpowerAverage(x10^6 Kwh)	394.847	399.637	391.403
		Wspill(m^3)	6.56 x10^8	7.21 x10^8	5.96 x10^8
		Z3(m)	63.02	63.07	63.16
5	Ban Mong Reservoir	Z2(m)	65.00	65.01	65.03
		NpowerAverage(x10^6 Kwh)	142.59	142.07	145.50
		Wspill(m^3)	5.68 x10^8	6.14 x10^8	3.29 x10^8
		Z3(m)	75.95	75.66	75.76
6	Ctr1(downstream of BanVe Reservoir)	SF	0	0	0
		SI	0	0	0
7	Ctr2 (downstream of Khe Bo Res.)	SFreq	0.0014	0.0229	0.0201
		SI	0	1.142	0.852
8	Ctr3 (downstream of BanMong Res.)	SFreq	0.024	0.036	0.038
		SI	0.367	0.610	0.213
9	Ctr4 (DuaStation)	SFreq	0	0	0
		SI	0	0	0
10	Ctr5(Yen Thuong Station)	SF	0.002	0.015	0.005
		SI	0	0	0
11	Ctr6(NamDanPumpStation)	H	>= 1.12 m	>= 1.12 m	>= 1.12 m

NpowerSum (Kwh): Yearly hydroelectric power output, Z2 (m): Reservoir water level at the end of dry season, Wspill (m^3): Spill flow, Z3 (m): Reservoir water level at the end of flood season, NpowerAverage: Yearly hydroelectric power output, SFreq: Shortage frequency, SI: Shortage Index, H: Required water level at pump station, Ctr1, Ctr2, Ctr3, Ctr4, Ctr5: Control point No1, No2, No3, No4. No5

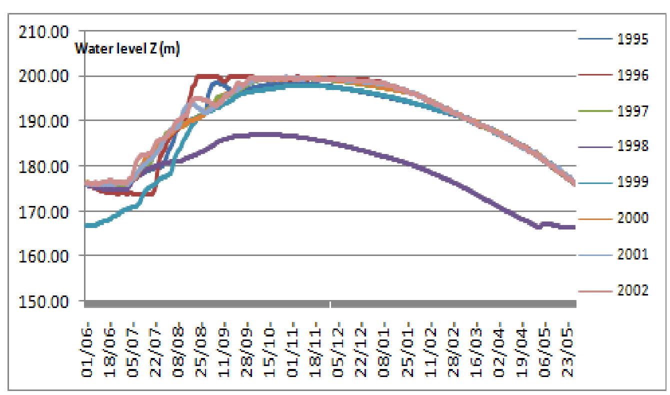

Fig. 10 Hydrograph of BanVe Reservoir water level from 1995-2003 (independent test operation under optimal RC)

Fig. 10 shows that the BanVe reservoir water level of from 1995-2003 (independent test operation under optimal RC) is lying between optimal URC and LUC. All criteria such as yearly hydroelectric power output NpowerSum, reservoir water level at the end of flood season Z3(m), reservoir water level at the end of dry season Z2(m), Spill flow Wspill (m^3), Shortage index SI, Shortage frequency SF are listed in Table III. It shows clearly that results obtained reservoir system operation under optimal RC is better than under the current RC

IV. Conclusions

Scientific basis and a method of building optimal multi-objective daily rule curves for hydropower reservoir system are presented. The optimal multi-objective daily rule curves can be constructed by reservoir system simulation and GA-KS. The method is successfully applied to the hydropower reservoir system in Ca River. The research shows that operating reservoir system in Ca River by using optimal multi-objective daily rule curves can be reached better criteria than using the monthly rule curves. By integrating the optimal multi-objective daily rule curves for hydropower reservoir system and fuzzy system for normal flood control, USACE emergency rule curve makes a complete tool that overcomes difficulties in operating a reservoir system

Acknowledgment

Author acknowledges the financial support by Institute of Meteorology, Hydrology and Environment and data-processing by Nguyen Thi Van at IMHEN. The author thanks to IMHEN project, titled "Development of Decision Support Framework on Water Resource Management, 2007" for providing the reservoir inflow data which are required to execute this work.

References

[1] Arxennhep G. X., "Economic Design of Water Resource", Textbook, Leningrad University of Meteorology and Hydrology, 1985.
[2] John Ch. and LI Ch., Real-Coded Genetic Algorithm for Rule-Based Flood Control Reservoir Management, Water Resources Management 12: 185–198, 1998, Kluwer Academic Publishers.
[3] Leo R. Beard, William K. Johnson, "Reservoir System Analysis for Conservation", HEC-IHD-0900, 1974.
[4] Cau, L. X., Emergency Operation Rule Curve, Journal of Meteorology and Hydrology, No 649 (1/2015) (in Vietnamese).
[5] Normantov I., Optimization of Mode of Hydropower stations with reservoir, Proceeding 6th International Conference on Hydroinformatics, 2004.
[6] Cau, L. X., Application of Genetic Algorithm in Hydrology, Journal of Meteorology and Hydrology, No 7(475)/2000 (in Vietnamese).
[7] Cau, L. X., Multi-objective Optimization of Water Resource by using Genetic Algorithm, Journal of Meteorology and Hydrology , No 8(476)/2000 (in Vietnamese).
[8] R. Wurbs, Optimization of Multi-Purpose Reservoir Operations, RD-34, HEC, 1991.
[9] Haimes Y. Y., Hall W. A., "Multi-objectives in Water Resource Systems Analysis: The Surrogate Worth Trade-off Method", Water Resources Research, Vol. 10, No. 4, 1974.
[10] Gregory A. W., An Indirect Method for Numerical Optimization Using the Kreisselmeier-Steinhauser Function, NASA Contractor Report 4220, 1989.
[11] Jianhua X., Jin X., Zehui S., Congfeng J. and Linqiang P., A Genetic Algorithm for solving Multi-Constrained Function Optimization Problems Based on KS Function, 2007 IEEE Congress on Evolutionary Computation (CEC 2007).
[12] Tuyen H. M., Development of Decision Support Framework on Water Resource Management in Ca River, Research Project Report, IMHEN, 5/2007