MAXIMIZATION OF HYDROPOWER USING STRATEGIES OF DIFFERENTIAL EVOLUTION

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***Abstract*:** Differential evolution algorithm as a family of evolutionary algorithms is extended to the maximization of hydropower generation in this study. Ten strategies of differential evolution are studied to determine the best strategy for the model. The model is adapted to the monthly operation of Vanderkloof dam in the Lower Orange river in South Africa. From the results, differential evolution strategy 8 (DE/best/2/exp) is the best for this model by generating 510 GWH of energy using 11,389.49 Mm^3 of water. It is concluded that differential evolution strategies with exponential crossover method are better than differential evolution strategy with binomial crossover method for the model presented in this study.

***Keywords*:** Differential Evolution, Hydropower, Optimization, Reservoir Operation

I. INTRODUCTION

Water resources management is a multi-objective optimization problem. It is a difficult task to estimate reservoir operating policies that maximize all the benefits provided by these reservoirs and also minimize their adverse impacts. It is a complex decision making process which will involve a number of variables, risks, uncertainties and also conflicting objectives. Reservoirs serve many purposes. They are used to drive turbines to generate electricity. They are used to supply water for irrigation, city and industrial uses and also for flood protection. Reservoirs may be built to satisfy a single purpose or multipurpose. Some of the purposes are conflicting in nature. For example for power generation, the reservoir should be as full as possible to increase the head, whereas for flood protection, it should be empty to provide for maximum storage of flood waters if flood occurs.

In the field of water resources engineering, particularly reservoir operations, genetic algorithm (GA) has been proved to be computationally superior to traditional methods like linear programming, non linear programming and dynamic programming. Two types of genetic algorithms, real-coded and binary-coded were applied to the optimization of a flood control reservoir model [1]. [2] explored the potential of alternative GA formulations in application to real time reservoir operation. They found that: (a) GA has the potentiality to large-finite horizon multireservoir system problems where objective function is complex; (b) GA needs no initial trial release policy; (c) easily applicable to nonlinear problems; and (d) GA can generate several solutions that are close to the optimum. Several other studies have shown the application of GA to water resources management [1-8].

Many optimization techniques have been applied to water resources management in the past. These include Linear Programming (LP); Nonlinear Programming (NLP); Dynamic Programming (DP); Stochastic Dynamic Programming (SDP); and Heuristic Programming such as Genetic Algorithms, Shuffled Complex Evolution, Fuzzy logic, and Neural Networks, Differential Evolution *etcetera*. [9] analyse multi-objective optimization problems and provide useful insights about solutions that are generated using population-based approached. Crop-planning problem as a multi-objective optimization model is formulated. Well-known multi-objective evolutionary algorithm called NSGAII and their proposed multi-objective constrained algorithm (MCA) are compared. The study by [10] unravels the complexity of water management institutions by analysing the interactive nature of actors and rules to a particular water-related problem, using a systems approach in a hamlet in the Indian Himalayas. [4] present a study to deal with the development and comparison of two models; a genetic algorithm (GA) and linear programming (LP) to be applied to real-time reservoir operation in an existing Chiller reservoir system in India. Their performance is analysed and from the results, the GA model is found to be superior to the LP model. Optimal water allocation and cropping patterns for the Jordan Valley, taking into consideration variations in expected incomes from agricultural production and rising water prices are studied by [11]. Their calculations were based on information available on water supplies, areas under irrigation and market conditions, and used linear programming models for determining solutions that maximize gross margins and minimize potential variations in these gross margins. The results indicated that optimizing cropping patterns and the allocation of irrigation water still has a substantial potential to increase the financial return from agriculture.

Applications of differential evolution in the area of water resources are found in the literatures [12-19]. The algorithm was found successful in these applications.

[20] gave the working principles of DE with single strategy. Later on, they suggested 10 different strategies namely, DE/rand/1/bin, DE/best/1/bin, DE/best/2/bin, DE/rand/2/bin, DE/randtobest/1/bin, DE/rand/1/exp, DE/best/1/exp, DE/best/2/exp, DE/rand/2/exp, DE/rand to best/1/exp. DE/x/y/z indicates DE for differential evolution, x is a string which denotes the vector to be perturbed, y denotes the number of different vectors taken for perturbation of x and z is the crossover method(exp: exponential; bin: binomial). A strategy that works out to be best for a given problem may not work well when applied to a different problem. The formulations of different strategies are given in Table 1.

The objective of this study is to experiment the ten strategies of differential evolution on the monthly operation of Vanderkloof dam for maximum hydropower generation. The monthly release to the turbines will be used downstream for irrigation purposes.

TABLE I:
FORMULATION OF THE TEN DIFFERENT STRATEGIES OF DIFFERENTIAL EVOLUTION

Strategy	Description	Formulation
1	DE/rand/1/bin	$v(g,i,j) = x(g,r_3,j) + F*[x(g,r_1,j) - x(g,r_2,j)]$
2	DE/best/1/bin	$v(g,i,j) = x(g,best,j) + F*[x(g,r_1,j) - x(g,r_2,j)]$
3	DE/best/2/bin	$v(g,i,j) = x(g,best,j) + F*[x(g,r_1,j)+x(g,r_2,j)-x(g,r_3,j)-x(g,r_4,j)]$
4	DE/rand/2/bin	$v(g,i,j) = x(g,r_5,j) + F*[x(g,r_1,j)+x(g,r_2,j)-x(g,r_3,j)-x(g,r_4,j)]$
5	DE/rand-to-best/1/bin	$v(g,i,j) = x(g,i,j) + F*[x(g,best,j)-x(g,i,j)] + F*[x(g,r_1,j)-x(g,r_2,j)]$
6	DE/rand/1/exp	$v(g,i,j) = x(g,r_3,j) + F*[x(g,r_1,j) - x(g,r_2,j)]$
7	DE/best/1/exp	$v(g,i,j) = x(g,best,j) + F*[x(g,r_1,j) - x(g,r_2,j)]$
8	DE/best/2/exp	$v(g,i,j) = x(g,best,j) + F*[x(g,r_1,j)+x(g,r_2,j)-x(g,r_3,j)-x(g,r_4,j)]$
9	DE/rand/2/exp	$v(g,i,j) = x(g,r_5,j) + F*[x(g,r_1,j)+x(g,r_2,j)-x(g,r_3,j)-x(g,r_4,j)]$
10	DE/rand-to-best/1/exp	$v(g,i,j) = x(g,i,j) + F*[x(g,best,j)-x(g,i,j)] + F*[x(g,r_1,j)-x(g,r_2,j)]$

II. DESCRIPTION OF THE DAM

The Vanderkloof dam is the second largest storage reservoir in South Africa with a capacity of over 3 200 million m^3. It is an important part of the Orange River Project (ORP). Water released from the Gariep Dam, which is about 130 km upstream of the dam, is either transferred through the Orange/Riet Canal to the Riet River basin or released downstream through the two hydropower generators. The combined capacity of the two installed generators is 240 MW at 120 MW each at a discharge of about 200 m^3/s and a total of 400m^3/s. The dam is currently the highest dam in South Africa with a wall height of 107 m and a crest length of 765 m. There are four gates installed in the wall and can discharge up to 8 500 m^3/s in total through the flood sluices which are positioned on the left flank of the dam. One of the main objectives of the ORP is to increase the value of the South African agricultural production to make provision for the establishment of a large number of irrigation farms. The operation of the dam for maximum irrigation benefit therefore cannot be overemphasised.

III. METHODOLOGY

The objective of this study is to maximize the hydropower generation at Vanderkloof dam. The water released for hydropower will still be used downstream the Orange River for irrigation. The two installed turbines have a combined capacity of 240MW. The constraints of this model are the mass balance constraints of storage, mass balance constraints of inflows, terminal constraints, storage head relationshipand reservoir storage capacity. The description of the objective function and the constraints are given below:

Objective function:

$$maximize \sum_{t=1}^{12} E(\eta H_t RT_t) \qquad (1)$$

Subject to these constraints:

$$S_t = S_{t-1} + I_t - RT_t - SP_t - EV_t \qquad (2)$$

$S_t \leq$ Reservoir capacity (3)

$S_t \geq S_0$ (4)

$S_t, SP_t, RT_t, H_t \geq 0$ (5)

E - is the hydropower energy

H_t - is the height of water above the turbine at the end of month t which has non-linear correlation with the volume of water in the reservoir. It is also dependent on the shape of the reservoir and the position of the turbine

η - the efficiency of the turbines

RT_t - Volume of water released to the turbines in month t

S_t - Reservoir storage at the end of month t

S_0 - Starting end of period storage

I_t - Inflow to the reservoir in month t

SP_t - Water spill at month t

The objective function in equation (1) and the constraints in equations (2) to (5) were solved using the ten different strategies of differential evolution.

IV. RESULTS AND DISCUSSION

Figure I presents the number of iterations before convergence for different strategies of differential evolution. It is found that strategies with exponential crossover method (strategies 6 to 10) perform better than strategies with binomial crossover method (strategies 1 to 5). Strategy 6 (DE/rand/1/exp) is the worst strategy in terms of number of iterations before convergence with 1901 number of iterations before convergence. Strategy 8 (DE/best/2/exp) is the best with 5 as the number of iterations before convergence. This is followed by strategy 10 with 40 as the number of iterations before convergence.

FIGURE I:
NUMBER IF ITERATIONS BEFORE CONVERGENCE FOR DIFFERENT STRATEGIES OF DIFFERENTIAL EVOLUTION

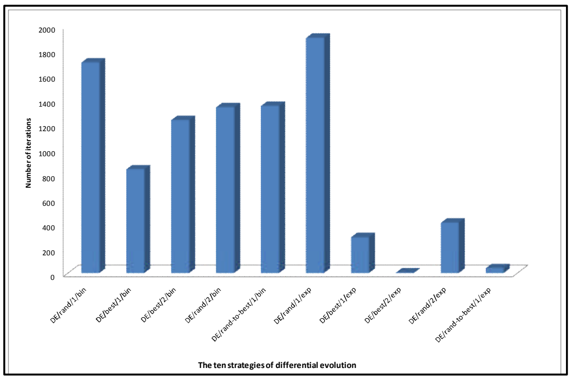


Figure II presents the total hydropower energy generated by the ten strategies of differential evolution over 12 months period. Strategy 8 generates 510.17 GWH of energy which is the highest of all the ten strategies. Strategy 3 generates the lowest energy of 467.46 GWH. From the analysis of the results in figure 2, it is found that strategies with exponential crossover method (6 to 10) performs better than strategies 1 to 5 which use binomial crossover method.

FIGURE II:
TOTAL HYDROPOWER FOR TEN STRATEGIES OF DIFFERENTIAL EVOLUTION

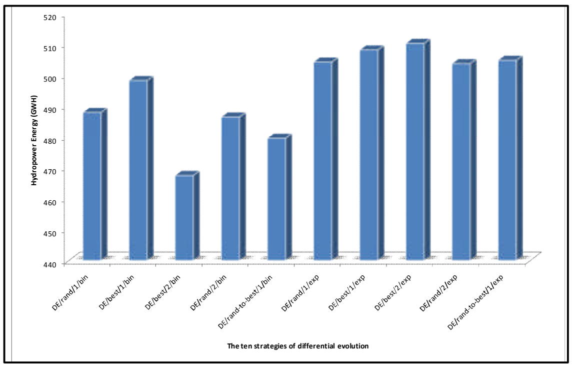


Figure III presents the total number of water use for hydropower generation for the ten strategies. It is found that differential evolution strategies with exponential crossover method use more volumes of water for hydropower than differential evolution strategies 1 to 5 with binomial crossover method. This is obvious because more volume of water use will result in more power generated.

The improvement in hydropower energy generated for the ten strategies is given in figure IV. The figure shows progression in hydropower generation in different generations of 300, 600, 900 and 1200. It is found that the progression is slower in differential evolution strategies with exponential crossover. The reason for this is that they converge quickly before the iteration gets to the maximum generation of 2000.

Monthly water releases for hydropower generated by different strategies of differential evolution are given in figure V. Strategies 1 to 5 show many variations in the monthly water releases than strategies 6 to 10.

FIGURE III:
TOTAL WATER VOLUME USED FOR TEN STRATEGIES OF DIFFERENTIAL EVOLUTION

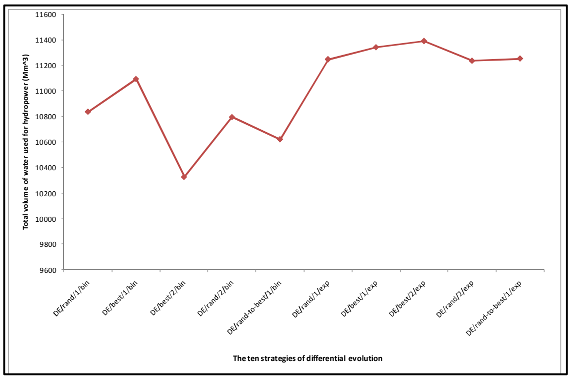


FIGURE IV:
IMPROVEMENTS IN HYDROPOWER ENERGY GENERATION OVER GENERATIONS

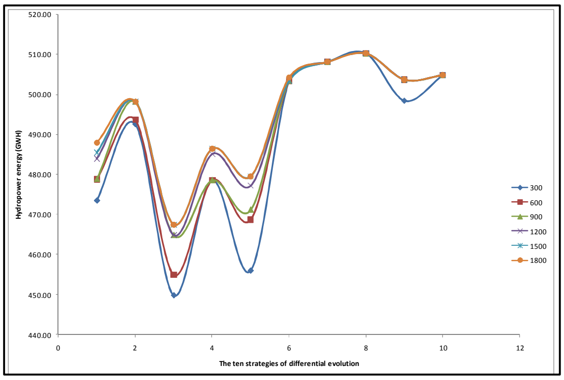
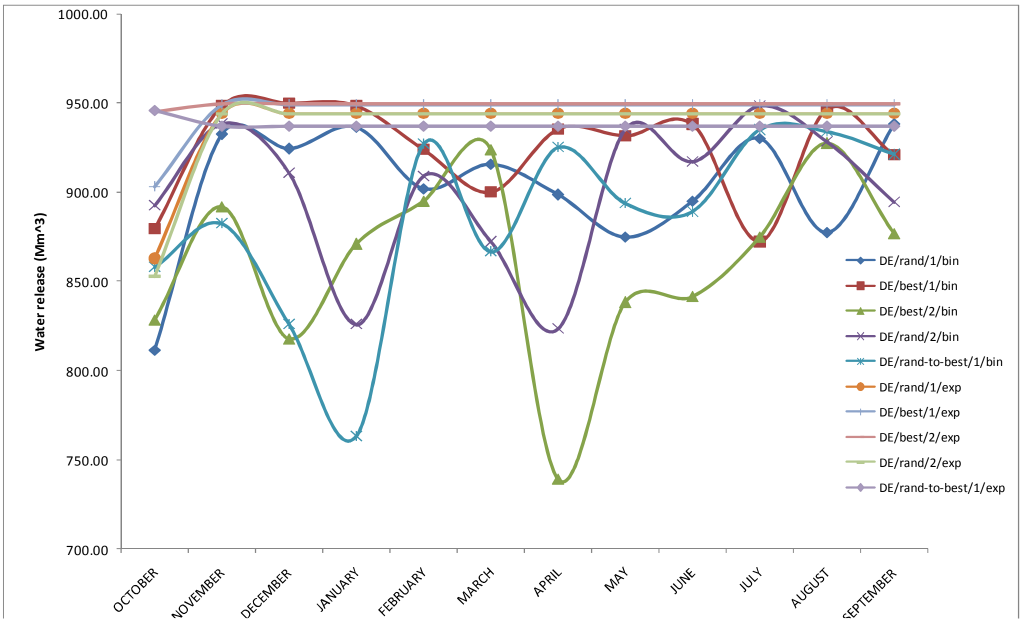


FIGURE V:
MONTHLY WATER RELESE FOR HYDROPOWER GENERATED BY DIFFERENT STRATEGIES OF DIFFERENTIAL EVOLUTION



V. CONCLUSION

The results generated in this study are very useful for the operators of Vanderkloof dam in maximizing hydropower generation. The hydropower is cheaper than other methods of power generation like coal fired power stations used presently in South Africa for 90% of power generation. Moreover, water is renewable unlike coal that is consumed. Hydropower is only used for peaking current generation. If it is possible to generate more electricity than presently generated, more revenue will be generated for Eskom. Recently, South Africa is experiencing shortages in power supply. If this study can be extended to manage power generation in the two hydropower reservoirs in the country (Gariep and Vanderkloof dams) to operate the two dams in series for power generation, it will be beneficial. Moreover, multi-objective optimization techniques can be extended to this study.

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