UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION OF OPERATIONS OF RESERVOIR SYSTEMS FOR HYDROPOWER GENERATION IN TIGRIS RIVER BASIN, IRAQ

YOUSIF HASHIM ABDULLAH AL-AQEELI

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By

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Thesis Submitted to the School of Graduated Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the degree of Doctor of Philosophy

August 2016

DEDICATION

To the dearest to my heart, my mother and father
To my lovely wife
To my son and daughters lovers to my heart
To my dear brothers
To my dear sister
To my lovely wife's family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

OPTIMIZATION OF OPERATIONS OF RESERVOIR SYSTEMS FOR HYDROPOWER GENERATION IN TIGRIS RIVER BASIN, IRAQ

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August 2016

Chairman : Samsuzana Abd Aziz, PhD
Faculty : Engineering

The aim of the study was to determine the optimal operation policies for the various combinations of up to four reservoirs (Mosul and Dokan reservoirs are currently in operation, Bekhma reservoir is under construction while Makhoul reservoir is under planning phase) along the Tigris river basin in Iraq for the purpose of optimally generating hydroelectric power, given the constraints pertinent to the area. A genetic algorithm optimization model (GAOM) was coded in the Matlab work environment to determine the optimal operating policy for a single reservoir to maximize the annual hydropower generation. Two algorithms were next formulated and used independently in the GAOM to improve the performance of the Mosul reservoir in Iraq, during 20 years of operation. The performances of these two algorithms were evaluated through comparing their optimal values. The GAOM achieved an increase in hydropower generation in 17 years of the 20 years with the second algorithm being the better. To determine the effect of precipitation and evaporation, their volumes were taken into consideration in the continuity equation, using the second algorithm. In this case, the obtained optimal values were decreased in all of the scenarios compared with ignoring the volumes of precipitation and evaporation. A simulation model (SM) for the Mosul reservoir was formulated by using the SIMULINK technique in the MATLAB environment. The r^2 and NSE are 0.92 and 0.87 respectively in comparison of elevations, and 0.81 and 0.77 respectively in comparisons of hydropower generated. Adopting the second algorithm and taking into consideration the evaporation and precipitation, the GAOM and SM of Mosul reservoir were combined. In this combination, the GAOM identified the optimal operation policy, while the SM adopted this optimal operation policy to evaluate the performance of GAOM calculations through comparing the three parameters; powers, elevations and storages in order to confirm the calculations of GAOM. In all of these comparisons, the coefficient of determination was 0.99.

Two operational strategies in the combination of GAOMs and SMs were used to determine the optimal operation policies for the multi-reservoir system located on the Tigris river basin in Iraq. In the first strategy, the target storage at the end of final

month is equal to, or above the minimum operational storage; and for the second strategy it is equal to, or above the initial storage. For each strategy, the performances of operation the reservoirs individually; as a dual-reservoir system; as a three-reservoir system and as a four-reservoir system were compared in terms of annual hydropower generation based on the three groups of annual inflows: minimum, average, and maximum during twenty years. Those operational situations where: firstly, running of Mosul and Dokan reservoirs, secondly, running of Mosul, Dokan and Bekhma reservoirs, and thirdly, running of Mosul, Dokan, Bekhma and Makhoul reservoirs. According to the values of T-test obtained, the results indicated that only using the first strategy and operating Mosul, Dokan, Bekhma and Makhoul reservoirs were significant in favor of running the reservoirs as one entity. The two strategies mentioned previously were also used in the combined GAOMs and SMs to determine the optimal operation policies for the multi-reservoir system in the case of using a new storage of Makhoul reservoir. For each strategy, the performance of the operation of the multi-reservoir system was assessed through comparing the annual hydropower production a prior to and after having used this new storage by relying on three modes of annual inflows, minimum, average, and maximum annual inflows. All of these comparisons were done in two cases: operating the reservoirs individually and as one system. Through using the first and second strategies, the hydropower production increased by good percentages through using those three modes of annual inflows. In addition, for each strategy, the performance of this multi-reservoir system was evaluated according to that new storage of Makhoul. In this evaluation, the annual hydropower production by operating the reservoirs individually and as one system were compared by using those three modes of inflows according to T-test. The results indicated that the differences between the hydropower generated were significant in favor of operating the reservoirs as one system through using the first strategy, while were non-significant by using the second strategy. The parameters of evaporation and precipitation must include in the continuity equation when using or creating a model simulates the dynamic processes of water storage system. Hybrid model, consists of GAOM and SM, was created. This model has high reliability and can be used in real applications with various storage systems.

Keywords: reservoir systems, optimization, simulation, optimal operation policy, genetic algorithms, Matlab, Simulink, hydropower generation, Tigris river basin, Iraq.

Abstrak tesis yang dikemukakan kepada Senat Universiti Puta Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGOPTIMUMAN OPERASI SISTEM RESERVOIR FOR HIDRO GENERASI DALAM TIGRIS LEMBANGAN SUNGAI, IRAQ

Oleh

YOUSIF HASHIM ABDULLAH AL-AQEELI

Ogos 2016

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Tujuan kajian adalah untuk menentukan dasar operasi yang optimum untuk pelbagai kombinasi sehingga empat buah takungan (Mosul dan Dokan sedang beroperasi pada masa kini, Bekhma sedang dibina manakala Makhoul di peringkat perancangan) sepanjang Sungai Tigris di Iraq untuk tujuan menjana kuasa hidroelektrik secara optimum, memandangkan kekangan berkaitan kawasan itu. Sebuah model pengoptimuman algoritma genetic (GAOM) dikodkan dengan persekitaran-kerja Matlab demi untuk menentukan dasar beroperasi optimum untuk satu takungan bagi memaksimumkan penjanaan tenaga hidro tahunan. Dua algoritma berikutan kemudian diformulasikan dan diguna secara bebas di dalam GAOM untuk meningkatkan prestasi takungan Mosul di Iraq, menggunakannya dalam 20 buah scenario (tahun) pengendalian masa nyata. Persembahan dua algoritma tersebut telah dinilaikan melalui membandingkan nilai optimum dihasilkan, pada mulanya dengan nilai cerapan, dan kemudian dengan satu sama lain semasa semua scenario digunakan. GAOM telah mencapai satu peningkatan penjanaan tenaga hidro dalam 17 tahun daripada 20 tahun berkenaan, menggunakan dua algoritma itu, yang mana tertunjuk bahawa algoritma kedua yang lebih baik. Demi untuk menentukan kesan pemendakan dan penyejatan, isipadu masing masing diambil kira di dalam persamaan keselanjaran, menggunakan algoritma kedua. Dalam kes ini, nilai optimum yang diperolehi berkurangan dalam semua senario berbanding dengan mengabaikan isipadu pemendakan dan penyejatan. Satu model simulasi (SM) untuk takungan Mosul telah dirumuskan menggunakan teknik SIMULINK dengan persekitaran MATLAB. r^2 and NSE ialah 0.92 dan 0.87 masing masing dalam perbandingan ketinggian paras air, dan juga bernilai 0.81 dan 0.77 masing masing dalam perbandingan penjanaan kuasa hidro. Dengan algoritma kedua serta mengambil kira penyejatan dan pemendakan, GAOM dan SM takungan Mosul telah digabungkan. Dalam gabungan ini, GAOM mengenal pasti dasar operasi yang optimum, manakala SM mengamalkan dasar operasi optimum ini untuk menilai prestasi GAOM melalui membandingkan tiga parameter iaitu; kuasa yang dihasilkan, paras ketinggian dan storan untuk mengesahkan pengiraan GAOM. Dalam kesemua perbandingan,pekali penentuan adalah 0.99.

Dua strategi dalam gabungan GAOMs and SMs digunakan untuk menentukan dasar operasi yang optimum untuk pelbagai system takungan terletak di dalam lembangan Sungai Tigris di Iraq. Dalam strategi pertama, sasaran storan pada hujung bulan lepas di ambil sebagai sama dengan, atau melebihi storan operasi minimum; dan untuk strategi kedua ia sama dengan, atau melebihi simpanan pada mulanya. Untuk setiap strategi, persembahan takungan air, operasi secara individu; sebagai sistem takungan berdua; sebagai sistem takungan bertiga atau sebagai sistem takungan berempat telah dipertandingkan dalam soal penjanaan tenaga hidro tahunan berdasarkan tiga kumpulan aliran masuk tahunan: minimum, sederhana, dan maksimum sepanjang jangkamasa dua puluh tahun. Situasi operasi merangkumi: pertama sekali, operasi Mosul bersama Dokan, keduanya, operasi bersama Mosul, Dokan and Bekhma, dan ketiganya, operasi bersama Mosul, Dokan, Bekhma and Makhoul. Menurut nilai hasil ujian T yang diperolehi, keputusan menunjukkan bahawa hanya dengan menggunakan strategi pertama berserta dengan beroperasi Mosul, Dokan, Bekhma and Makhoul berasingan secara individu, dan juga sebagai satu sistem takungan berempat penting menyokong mengoperasikan takungan air sebabagi satu entiti. Dua strategi tersebut terlebih dahulu juga digunakan dalam gabungan GAOMs and SMs untuk menentukan dasar operasi optimum bagi system multi takungan didalam hal menggunakan satu storan baru takungan Makhoul. Untuk setiap strategi, prestasi operasi system pelbagai combinasi takungan ditaksir melalui membandingkan pengeluaran kuasa hidro tahunan sebelum dan setelah menggunakan storan baru ini dengan bergantung pada tiga corak aliran masuk tahunan iaitu: minimum, purata, dan maksimum. Kesemua perbandingan ini dibuat dalam dua kes: beroperasi takungan air secara individu dan kemudia sebagai satu sistem multi takungan. Melalui menggunakan strategi pertama dan kedua, pengeluaran kuasa hidro bertambah sebanyak peratusan yang baik melalui menggunakan ketiga-tiga mod daripada aliran masuk tahunan. Tambahan pula, untuk setiap strategi, prestasi system multi takungan ini dinilaikan berdasarkan storan baru di Makhoul. Dalam penilaian ini pengeluaran kuasa hidro tahunan, melalui operasi takungan berasingan secara individu dan melalui operasi sebgaia gabungan system takungan telah dipertandingkan dengan menggunakan tiga mod aliran masuk mengikut Ujian T .Keputusan menunjukkan bahawa perbezaan kuasa hidro dijana adalah penting dan sedia menyokong cadangan mengoperasikan takungan takungan air sebagai satu sistem gabungan menggunakan strategi pertama; manakala ialah tidak bererti sekirn menggunakan strategi kedua. Parameter penyejatan dan Kerpasan mesti termasuk dalam persamaan keselanjaran apabila menggunakan atau mewujudkan model yang menyerupai proses dinamik sistem penyimpanan air. model hibrid, terdiri daripada GAOM dan SM, telah dicipta. Model ini mempunyai kebolehpercayaan yang tinggi dan boleh digunakan dalam aplikasi sebenar dengan pelbagai sistem penyimpanan.

Kata Kunci: sistem takungan, simulasi, pengoptimuman, dasar operasi optimum, algoritma genetik, Matlab, Simulink, penjanaan kuasa hidro, lembangan sungai Tigris, Iraq.

ACKNOWLEDGEMENTS

My deepest graduate goes to the Most Merciful Allah S.W.T. Who granted me a knowledge help me to pursue my PhD degree in Malaysia.

The full version of this thesis would not have been possible without supporting of many people. I am very grateful to all those who supported me in the completion of this work and stand with me in all circumstances. I would like to extend my thanks to my supervisor, Dr. Samsuzana Abd Aziz, who provided me valuable advice, encouragements and support in order to continue and complete my work. I would like to thank my former supervisor, Dr. Professor Lee Teang Shui, who support and advise me during the first three semesters, before he retired. Gratitude and appreciation to the other members of my committee, Dr. Badronnisa bt. Yusuf and Dr. Aimrun Wayayok, for the suggestions and insights which contributed to strengthen of the thesis.

I want to thank my parents, my father, who spent his life in our care and my mother for her prayers and supplication to Allah S.W.T. to help me in my studies. I wish to thank my dear wife for the kind words and support. To my brothers, my friends, thank you for your kind words and support.

I certify that a Thesis Examination Committee has met on 11 August 2016 to conduct the final examination of Yousif Hashim Abdullah Al-Aqeeli on his thesis entitled "Optimization of Operations of Reservoir Systems for Hydropower Generation in Tigris River Basin, Iraq" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

GAOM	Genetic Algorithm Optimization Model
SM	Simulation Model
GAOMs	Genetic Algorithm Optimization Models
SMs	Simulation Models
GA	Genetic Algorithm
GAs	Genetic Algorithms
CI	Computational Intelligence
EC	Evolutionary Computation
EP	Evolutionary Programming
ES	Evolution Strategies
x_n	Real variable in the dynamic real representation
ge_n	Genes
in_n^*	Integer variable in the real representation of integer variables
$fitness$	Fitness function
f_{min}	Minimum observed value of the objective function up to generation (t)
f_{max}	Maximum observed value of the objective function up to generation (t)
$Pr(\vec{v_i})$	Selection probabilities in Roulette-wheel selection
$Pr_{lr}(i)$	Selection probabilities in Rank-based selection (Linear ranking)
$gene_m^{nm}$	Gene mutated by Non-Uniform Mutation
$gene_m^{bm}$	Gene mutated by Breeder Mutation
m.a.s.l	Meter above sea level
MCM	Million cubic meter
m^3/sec	Cubic meter per second

mm	Millimeter
E	Energy in Gigawatt hour (GWhr)
Dt	Number of hours in the time period
P_t	Power in megawatts (MW) in time period (t)
k	Constant (0.003)
RP_t	Release from the tunnels connected to the hydroelectric station (MCM)
H_t	Average head in the time period (meter)
t	Time period (month)
S_{t+1}	Storage at beginning of time period (t + 1)
S_t	Storage at beginning of time period (t)
I_t	Inflow during time period (t)
R_t	Outflow during time period (t)
S_{min}	Minimum operational storage
S_{max}	Maximum operational storage
PC	Capacity of tunnels connected to the hydroelectric station
D_t	Monthly water requirements
HC	Hydraulic capacity downstream the reservoir
S_{e12}	Storage at the end of the last month
S_T	Target storage at the end of the last month
Ev_t	Evaporation in time period (t)
Pr_t	Precipitation in time period (t)
Sp_t	Seepage from reservoir in time period (t)
r^2	Coefficient of determination
o_i	Observed values in duration i

e_i	Calculated values in duration i
$\bar{o}$	Average of observed values
$\bar{e}$	Average of observed values
n	Number of values
NSE	Nash-Sutcliffe efficiency
I	Number of reservoirs
T	Total time period (12 months)
$P_{i,t}$	Power (megawatts) in time period (t) for each reservoir (i) of the multi-reservoir system
ST 1	First strategy
ST 2	Second strategy

CHAPTER I

INTRODUCTION

1.1 Introduction

An operation research model generally consists of three basic components: (1) identification of specific decision variables, (2) the objective for optimization and (3) the constraints that the solution must satisfy (Taha, 2011). Thus, the main function of optimization models is to search through a large number of possible solutions. The intention is to derive numerical values of decision variables. Such a procedure will maximize or minimize the objective function value under all considered restrictions.

In water resource systems, integrated strategies are determined for storage system operations. This is the current scientific research trend regarding the satisfaction of requirements. In the operation and management of storage systems, it is essential to combine models of optimization and simulation through software related to the field. Several of these software were explained by Wurbs (2012). Optimization and simulation models are effective tools for reservoir systems analysis. Optimization models formulate a mathematical algorithm to determine decision variable values that maximize or minimize an objective function. Combining both models (Rani and Moreira, 2010) produces the best results. Optimization models seek to find solutions to satisfy the decision maker's pre-specified criteria. Simulation models provide a clear picture of what will occur if the solution is adopted. Optimization models work as a filter in specifying the ideal solution among a large number of possible solutions, and simulation models evaluate the performance of the adopted solution (Nandalal and Bogardi, 2007).

Reservoir operation requires operators to manage the frequency and quantity of the water releases. The reservoir is designed to address different requirements at downstream, such as water supply, hydropower production, recreation, and flood control. Thus, operations must meet the demands efficiently and reliably. Because the inflows and volumes of the storage are unconfirmed in the future, it is important to determine the best reservoir releases for a group of possible inflows and storage conditions (Loucks et al., 2005). An evolution tool is used to solve an unusual problem as stated above. Holland (1975) was the first to propose the genetic algorithm, which is a computational model that simulates natural evolution to solve various types of problems (Ribeiro Filho et al., 1994). The genetic algorithm is one of the optimization methods frequently used in frameworks of management and water storage systems operation. Wurbs (2005) stated that the greatest benefits from reservoir storage are the following: (1) maximization of hydropower generation, (2) maximization of the advantages from irrigation projects, and (3) reduction of flood damage, etc. These benefits are represented by objective functions with values that change as decision variables change.

The present study combines the optimization and simulation models to derive an optimal operating policies for the multi-reservoir system located at the Tigris river basin in northern Iraq, which comprises four reservoirs. The objective function will maximize annual hydropower generation through identifying ideal values of releases and noting the corresponding levels from the reservoir. A genetic algorithm optimization model (GAOM) was coded and a simulation model (SM) was built for the storage system using the SIMULINK technique. The GAOM was used to determine the optimal operating policies for this storage system, while the SM was used to predict the system behavior and validate the operating policies provided by the optimization model. These procedures were conducted in the Matlab work environment.

1.2 Statement of the Problem

Water storage systems have been established to achieve many goals. Conducting periodical assessments of these systems is necessary to improve their performance, as a result of population growth and the expansion of the water supply projects that belong to the municipality as well the development or creation of irrigation projects that derive their water from the storage systems (Jothiprakash and Shanthi, 2006), (Sattari et al, 2009), (Khan et al, 2012), in addition to adapt to the effects of climate change (Fayaed et al, 2013). The performance of water storage systems should be re-assessed to discover new rules of improvement and to consider the possible addition of new storage units. These improvements can be achieved through the identification of new optimal operation policies. New software and techniques can be used to calculate the highest benefit while considering all the restrictions imposed by the new system structure. These new developments were applied to the Mosul and Dokan reservoirs. Identifying new operational policies for storage system performance of the Bekhma and Makhoul reservoirs under different scenarios is necessary because they will be added to the storage system consists of Mosul and Dukan reservoirs.

Iraq suffers from a severe electricity processing shortage (IAU-UNDP, 2012), (Rashid, 2012), (Kazem and Chaichan, 2012) and (Al-Khatteeb and Istepanian, 2015). The Ministry of Electricity reports that Iraq only generates 8×10^3 of the 13 to 15×10^3 MW of currently required power (IAU-UNDP, 2012). The objective function of these new operating policies is to maximize the hydropower generation from storage systems by combining the optimization and simulation models. Based on its wide application in solving such these issues, the genetic algorithm (GA) was used to formulate an optimization model (Wardlaw and Sharif, 1999), (Karamouz et al., 2004), (Lin et al., 2005), (Cheng et al., 2008), (Hınçal et al., 2011), (Sreekanth et al., 2012), and (Li and Qiu, 2015). Assessing hydropower generation through this method will provide insight regarding the potential of the storage system to generate hydropower.

1.3 Objectives of the Study

This study aims to identify the optimal operation policies for the multi-reservoir systems located at the Tigris river basin in Iraq by combining the optimization and simulation models.

Specific Objectives

1. To investigate strategies of reservoir systems operations.
2. To create combined optimization and simulation models for the multi-reservoir systems located in the Tigris river basin, Iraq in different forms of operation:
   a. Combining the optimization and simulation models to represent each reservoir in the system individually (Mosul, Dokan, Bekhma, and Makhoul reservoirs).
   b. Combining the optimization and simulation models to improve the efficiency of the current storage system particularly the Mosul and Dokan reservoirs
   c. Combining the optimization and simulation models for the storage system for the Mosul, Dokan, and Bekhma reservoirs to gauge their combined performance in one system.
   d. Combining the optimization and simulation models for the storage system of all four reservoirs (Mosul, Dokan, Bekhma, and Makhoul) to find the optimal operating policy when they work as one system.
3. To test the optimal individual and simultaneous operating performance of the reservoirs of that multi-reservoir systems (dual reservoirs, three reservoirs and four reservoirs).
4. To determine and assess a new storage volume for the Makhoul reservoir.

1.4 Scope of the Study

This study uses GAOM and SM combinations to identify optimal operation policies for the multi-reservoir systems located in the Tigris river basin. These multi-reservoir systems include a dual-reservoir system, a three-reservoir system, and a four-reservoir system. The following describe the detailed scope of this study:

1. Collecting the data of the Mosul reservoir that represents the monthly inflow, outflow, elevation, and hydropower generation.
2. Collecting the monthly inflow for Dokan reservoir, as well the observed flow at the Fatha and Aski Kalak stations.
3. Collecting the hydraulic properties for the reservoirs of Mosul, Dokan, Bekhma, and Makhoul.
4. Formulating a GAOM for a single reservoir (Mosul reservoir) in the workspace of the Matlab environment through two algorithms.
5. Evaluating the performance of these two algorithms independently of operating the GAOM prior to adding the evaporation and precipitation to the continuity equation.
6. Adding the evaporation and precipitation to the continuity equation and re-assessing the performance of the GAOM by using the most appropriate algorithm.

7. Formulating and evaluating a SM for a single reservoir (Mosul reservoir).
8. Combining a GAOM and SM for a single reservoir (Mosul reservoir) to evaluate the calculation of the GAOM.
9. Building the combination of GAOMs and SMs for each reservoir individually and for multi-reservoir systems (dual-reservoir, three-reservoir, and four-reservoir) to identify the optimal operation policies.
10. Maximizing the storage volume of Makhoul reservoir and re-assessing the performance of this reservoir by combining its GAOMs and SMs individually and with three other reservoirs as one entity.

1.5 Tools and Data

1. Matlab program (2013b).
2. Computer with sufficiently high specifications to program the GAOM and SM using Matlab.
3. The hydraulic properties of the system reservoirs that include the following:
   a. Designing elevations related to the storages in the reservoirs.
   b. Designing volumes of the storage in the reservoirs.
   c. The capacity of different outlets of the system reservoirs.
   d. The elevation-storage-area curves that belong to those four reservoirs.
   e. The maximum capacity of hydropower generating stations.
4. Data representing the monthly flows during a period of 240 months from October 1989 to December 2009 in the first four stations (a, b, c and d), as well this data including the flows for a period of 120 months from October 1989 to December 1999 (see points e and f):
   a. The monthly inflows of Mosul reservoir.
   b. The monthly outflows from Mosul reservoir.
   c. The monthly inflows of Dokan reservoir.
   d. The monthly flows at Aski Kalak station, located on the Greater Zab near Bekhma reservoir.
   e. The monthly outflows from Dokan reservoir.
   f. The monthly flows at the Fatha station, located along the Tigris river near the site of the Makhoul reservoir.
5. The following data from the Mosul reservoir exclusive to the 240 months of October 1989 to December 2009:
   a. Monthly hydropower generated.
   b. Monthly storage elevations.
   c. The volumes of storage at the first day for every water year (each 1 October for every year) from 1 October 1989 to 1 October 2009.
6. Other data related to the system reservoirs:
   a. Monthly rainfall rate as a depth on the system reservoirs.
   b. Monthly evaporation rate as a depth from the system reservoirs.
   c. Monthly water requirements downstream the system reservoirs that comprise demands of irrigation, fishery development, forestry, the population, industrial development, thermal energy, and the environment.

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