Short-Term Hydro Generation Scheduling Of Cascade Plants Operating On Litani River Project - Lebanon

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Abstract—**Short-term hydro generation optimal scheduling of cascade hydropower stations is a typical nonlinear programming problem that minimizes the deviation between the produced power and the grid requirement while satisfying hydraulic and electrical constraints. In this work, the main objective is to find the optimal hourly water discharge rate of each hydro station in a multi-reservoir system to minimize the power deficit. The demanded load is then distributed among the working units of three cascade hydropower stations constructed on Litaini River - Lebanon: Markaba, Awali and Charles Helou. To achieve our goal, methods involving and joining data mining and mathematical programming will serve as a base for a Decision Support Tool (DST). Based on the DST features, a distributed control structure is implemented using a multiple software framework. MATLAB is used for mathematical optimization while LabVIEW is employed to develop Human Machine Interface (HMI) for sequential control.**

Keywords*—*Hydropower Planning, Cascade System, Mathematical Programming, MATLAB, LabVIEW, Simulation

I. INTRODUCTION

HYDRO-electricity constitutes one of the main inexhaustible sources of energy contributing about 72.8% of the world's renewable electrical energy production sector [1]. This clean and cheap energy is attracting more attention all over the world to overcome the increasing power demand. Further the awareness regarding the limitations of the fossil fuel reserves, have aroused for several years the necessity of presenting effective tools to optimize electricity production. In this sense, scheduling models represent a useful and vital tool for hydro-electric power systems operation and planning.

Despite being a mature technology, compared to other renewable energy sources, hydropower has still a significant potential mostly in cascade systems. In fact, to benefit from an existing water resource as much as possible, it is common to see several hydropower plants constructed on a same river and sharing the same water pool [2]. Thus, on the same river new plants can be subjoined and old ones can be upgraded, in order to increase electricity production and efficiency that can be achieved by intelligent operation and coordination.

Well, any mis-coordination among the operators of the power stations, spillages may occur and water may be wasted without being utilized for electricity generation. The use of forecasting algorithms on the expected water supply is definitely a good support for reaching optimal results.

For quite long time and still, Lebanon is suffering from an acute energy crisis, due to several reasons mainly: lack of domestic energy resources, reduced production capacities, growing demand for energy and bad energy management. In this paper, our aim is to present a better power management policy taking into consideration several hydraulic and electrical constraints. The Qaraoun reservoir in Lebanon is used as a case study. It is designed to generate hydropower from three power plants: Markaba, Awali and Charles Helou with an installed capacity of 190 MW. Although this capacity is representing only 10% of the total supply in Lebanon, it is used as an important source for grid regulation. However, through deep investigations carried on site, it was seen that the water release for electrical generation was performed based on personal expertise and according to the actual demand requirements set by "Electricité du Liban (EDL)", the sole electrical power supply distributor in Lebanon. Very few studies were carried on Qaraoun dam regarding optimal operation of hydropower plants. In that context, we came across two papers: [3] suggested a mathematical model to maximize the hydropower production from Markaba power plant at monthly steps, while [4] attempts to analyze the design of a pumping station and the performance of a hybrid wind-hydro power plant that could be implemented on Qaraoun dam, considered then as pumped hydro storage. The rareness of contributed work on that topic motivated us to investigate one of the most significant issues in power systems [5], [6]: Short-Term Hydro Generation Scheduling (STHGS), specifically the determination of the hourly scheduling of available hydro generating units over the planning horizon.

This STHGS tool will be used to aid and support the operation of the three cascade power plants Markaba, Awali and Charles Helou. According to [3], the present operational policy of the reservoir depends mainly on the released water to meet the highly variable demand of EDL as a support for thermally generated energy during peak hours of power consumption. To meet EDL demands, operation decisions depend on operators experience and knowledge rather on mathematical modeling and intelligent Decision Support Tool (DST). Indeed, this approach doesn't guarantee neither optimal nor reliable solution for the hydropower production.

Different methods have been adopted to solve the short-term operation scheduling problem of hydropower generation: Linear Programming (LP) [7], Mixed-Integer Linear Programming (MILP) [8], Mixed Integer Nonlinear Programming (MINLP) [9] and Dynamic Programming (DP) [10]. It should be noted that, the proposed STHGS model is a typical nonlinear mixed integer optimization problem. It involves a continuous variable assigned to water release through each turbine and a 0–1 binary variable that determines the startup and shutdown scheduling of the power units of the three plants during the planning period. According to [9], (DP) can find the optimal solution of STHGS problem theoretically, but it suffers from the “curse of the dimensionality” when dimension of the problem is large. On the other hand, the limited availability of meta-heuristic tools and the dullness of writing the code from scratch, testing and validation, turned our attention to an alternative approach. It is a matter of taking the advantage of the availability of (MILP) solvers in the market, a favorable way to solve (MINLP) model is by linearizing through a suitable change of variable technique to handle nonlinear functions. In fact, the linearized problem did not lose its accuracy or its essential properties.

The rest of the paper is organized as follows: Section II describes in details the hydropower system, while section III presents a simulation by the suggested (STHGS) tool, whereas the drawn conclusion of the study and the future work are presented in section IV.

II. HYDROPOWER CASCADE SYSTEM DESCRIPTION

Qaraoun Lake (Figure 1) is an artificial multi- purpose reservoir with a storage capacity of 220 millions of cubic meters, and is located in the southern region of the Beqaa Valley, Lebanon. It was created near Qaraoun village in 1959 by building a 61-meter-high concrete-faced rockfill dam (the largest dam in Lebanon) in the middle reaches of the Litani River (longest river in Lebanon). The reservoir is used for domestic water supply, hydropower generation (190 MW) and for irrigation of 1,400 ha of land in the Bekaa valley and 36,000 ha in the South of Lebanon.

Fig. 1. Qaraoun dam

A. Cascade System

A system is known as cascade hydropower system, when two or more hydropower plants are implemented in series such that the runoff discharge of one hydro power plant is used as the inflow of the next hydro power plant. Maximizing the benefit from the simultaneous operation of cascade hydropower plants impose a challenge for decision makers due to its complex nature. For instance, there are basically conflicts of interest among the structural safety, the water supply, the recreation, the flood control, and the environmental issues. In this work, the Litani project that is composed of Qaraoun dam along with the cascade power stations Markaba, Awali and Joun will be considered as a subject of the suggested application analysis. The following subsection presents a brief overview of the hydropower plants within the Litani project.

B. Litani Project Overview

The project involved is the construction of Qaraoun dam and diverting the Litani River through a system of tunnels inter-connecting three hydropower plants: Markaba (34 MW), Awali (108 MW) and Joun (48 MW). All the information addressed below were retrieved from the Litani River Authority (LRA) website [11].

- **Markaba:** The first power station in the network, it is located 660 m above sea level and 11 km away from the Qaraoun reservoir. It takes water in from the Qaraoun lake through Markaba tunnel cutting an underground distance 6.4 Km along the right riverbank.

- **Awali:** It is located in the basin of Bisri River, at 228.50 m above sea level. Its waterfall is located at an altitude of 400 m. Water from the Qaraoun lake, after it discharges from the turbines of Markaba station, join the water of Ain Zarqa and other springs, through a 17 Km tunnel crossing Jabal Niha-Jezzine all the way to its pool: Anan lake (capacity 170, 000 m^3). The basic role of Awali plant is regulating the frequency of the public transportation network related to the difference in consumption needs, within its power supply capacity.

- **Charles Helou :** It is located on the left bank of Awali river, 32 m above sea level. Its waterfall is located at an altitude of 194 m. It pulls, through a 6800 m tunnel, the water discharged by the turbines of Awali power plant, in addition to the water flowing from Bisri river to the balancing lake (capacity 300,000 m^3) at the foot of Awali power plant (Figure 2).

Further specifications associated with hydropower plants are addressed in Table I

Fig. 2. Left picture: Anan pond, Right picture: Awali station and Joun pond

At the final stage, water leaving Charles Helou is used for irrigating certain parts of the South-Lebanon, while the

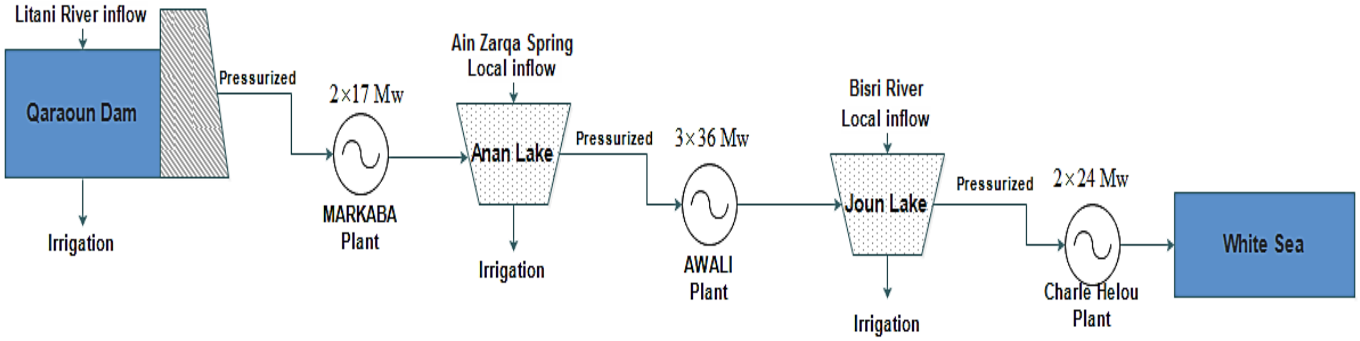


Fig. 3. A schematic draw of the complete cascade hydropower system

remaining water continue its way to the Mediterranean (Figure 3)

TABLE I. DATA ASSOCIATED WITH EACH PLANT

Plant	Turbine No/type	Installed Capacity(MW)	Discharge Capacity(m^3/s)
Markaba	2xFrancis	34	22
Awali	3xPelton	108	33
Charles-Helou	2xFrancis	48	33

C. *Current Qaraoun Reservoir Operation*

According to [12], more than 80% of the water in the Qaraoun Lake (or 180 million of cubic meters) are used to generate electricity in the Markaba, Awali and Charles Helou hydropower plants. Thus the priority of the stored water is electricity generation. As a matter of fact, the main task executed by Litani River Authority (LRA), the operator of the hydropower plants, is to meet highly variable electricity demand by EDL. However, during our technical investigation executed on Markaba and Awali hydropower plants, one can notice the following: 1- personal engagement in power plant operation is fundamental in start and stop sequencing of the electric generating units instead of being just monitors or repairmen; 2- lack of suitable equipment (data acquisition, distributed control ...); 3- decisions are based on person expertise. Well, the operator has become a part of the process where he has to understand the way the plants and each of their parts operate. Moreover, in the course of operational scheduling, calculations are manually performed due to lack of necessary automated instruments. Thus, the operation depends solely on the skills of the operator which increases the risks regarding safety and reliability of the power system leading to poor hydropower exploitation.

1) Hourly Operation: The exact timing of power generation and load profile estimates are provided by EDL, while the generation mechanism is LRA responsibility. Water release and on/off sequencing of the generators are set to meet the load profile by the aid of Table II and the algorithm presented in Figure 4.

TABLE II. POWER PRODUCTION VS DISCHARGE

Markaba		Awali		Charles Helou	
Power (MW)	Flow (m^3/s)	Power (MW)	Flow (m^3/s)	Power (MW)	Flow (m^3/s)
2	1.5	0	0.5	2	1.86
4	3	3.2	1	6	3.7
6	4.5	6.7	2	8	5
8	6	10	3	10	6.2
10	7.5	13	4	12	7.3
12	9	17	5	16	10
14	10.5	20	6	18	11.5
16	12	23	7	20	12.5
18	13.5	27	8	24	15
20	15	30	9	28	17.3
22	16.5	37	11	30	18.6
24	18	40	12	34	21
26	19.5	47	14	38	23.5
28	21	53	16	40	25
30	22	57	17	44	26.2
32	23	60	18	46	28.3
34	24	67	20	48	30
		70	21		
		72	22		
		76	24		
		80	26		
		88	28		
		94	30		
		98	32		
		108	34		

2) Current Operation Limitations: To suggest any Decision Support Tool (DST), it is important to understand the limitations of the current process so that any new operational plan can perform better in the course of reservoir operations. The limitations of the current decision practice can be summarized in the following:

- Operation is not optimal. It is based on trial and error method.
- Planning does not encompass any river forecast modeling, and thus, the process is subject to large errors given the substantial large variability in stream flow.
- Risk of spillage or flood. Water is lost without being utilized for electricity generation (Figure 5)
- Frequent on/off operation results in shortening the life of units.
- Risks concerning structural safety and recreation.

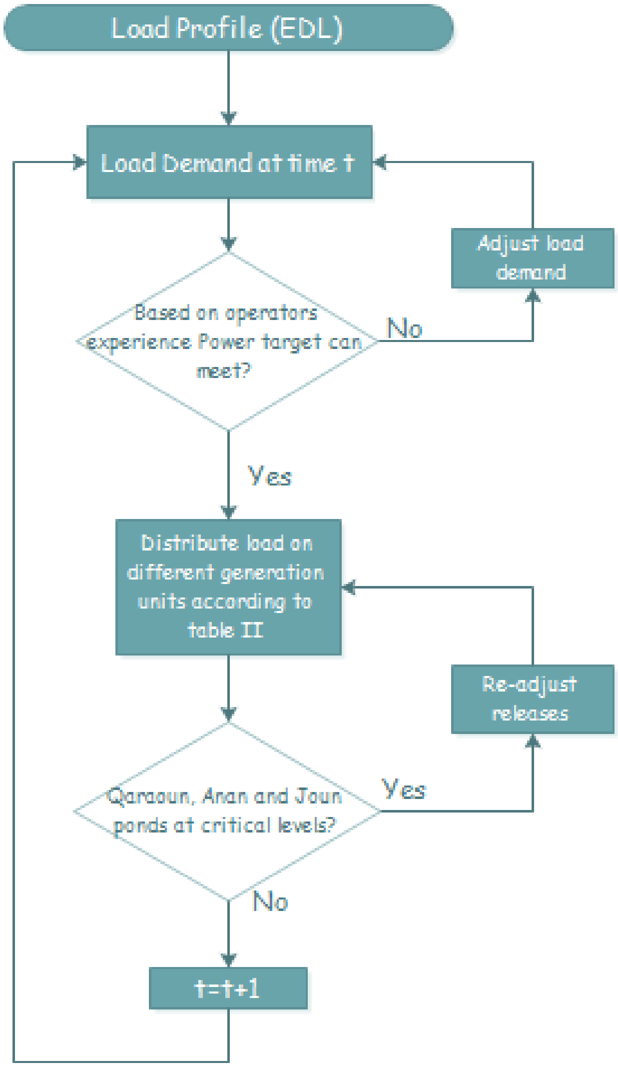
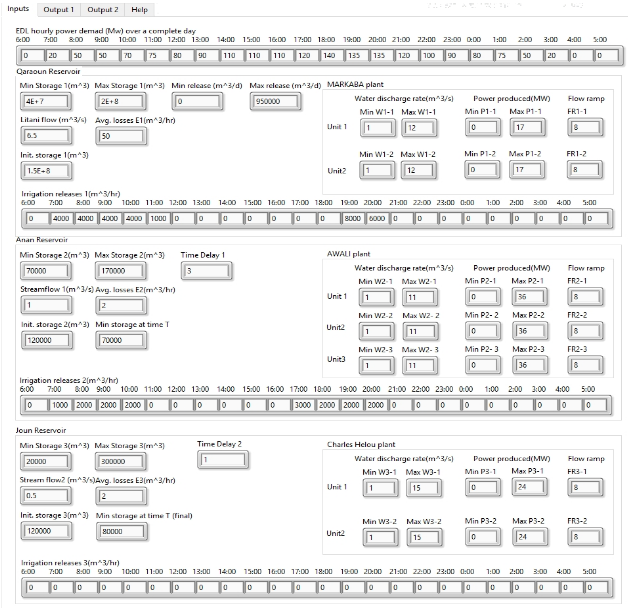


Fig. 4. The Operation Flow-chart implemented on the three hydropower plants: Markaba, Awali and Charles Helou

Fig. 5. Flood relief through the spillway of the Qaraoun dam



EDL hourly power demad (Mw) over a complete day

6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00	1:00	2:00	3:00	4:00	5:00
0	20	50	50	70	75	80	90	110	110	110	120	140	135	135	120	100	90	80	75	50	20	0	0

Qaraoun Reservoir

Min Storage 1(m^3): 4E+7
Max Storage 1(m^3): 2E+8
Min release (m^3/d): 0
Max release (m^3/d): 950000
Litani flow (m^3/s): 6.5
Avg. losses E1(m^3/hr): 50
Init. storage 1(m^3): 1.5E+8

MARKABA plant

	Water discharge rate(m^3/s)		Power produced(MW)		Flow ramp
	Min W1-1	Max W1-1	Min P1-1	Max P1-1	FR1-1
Unit 1	1	12	0	17	8
	Min W1-2	Max W1-2	Min P1-2	Max P1-2	FR1-2
Unit2	1	12	0	17	8

Irrigation releases 1(m^3/hr)

6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00	1:00	2:00	3:00	4:00	5:00
0	4000	4000	4000	4000	1000	0	0	0	0	0	0	0	8000	6000	0	0	0	0	0	0	0	0	0

Anan Reservoir

Min Storage 2(m^3): 70000
Max Storage 2(m^3): 170000
Time Delay 1: 3
Streamflow 1(m^3/s): 1
Avg. losses E2(m^3/hr): 2
Init. storage 2(m^3): 120000
Min storage at time T: 70000

AWALI plant

	Water discharge rate(m^3/s)		Power produced(MW)		Flow ramp
	Min W2-1	Max W2-1	Min P2-1	Max P2-1	FR2-1
Unit 1	1	11	0	36	8
	Min W2-2	Max W2- 2	Min P2- 2	Max P2-2	FR2-2
Unit2	1	11	0	36	8
	Min W2-3	Max W2- 3	Min P2- 3	Max P2-3	FR2-3
Unit3	1	11	0	36	8

Irrigation releases 2(m^3/hr)

6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00	1:00	2:00	3:00	4:00	5:00
0	1000	2000	2000	2000	0	0	0	0	0	0	3000	2000	2000	2000	0	0	0	0	0	0	0	0	0

Joun Reservoir

Min Storage 3(m^3): 20000
Max Storage 3(m^3): 300000
Time Delay 2: 1
Stream flow2 (m^3/s): 0.5
Avg. losses E3(m^3/hr): 2
Init. storage 3(m^3): 120000
Min storage at time T (final): 80000

Charles Helou plant

	Water discharge rate(m^3/s)		Power produced(MW)		Flow ramp
	Min W3-1	Max W3-1	Min P3-1	Max P3-1	FR3-1
Unit 1	1	15	0	24	8
	Min W3-2	Max W3-2	Min P3-2	Max P3-2	FR3-2
Unit2	1	15	0	24	8

Irrigation releases 3(m^3/hr)

6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00	1:00	2:00	3:00	4:00	5:00
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 6. HMI Display - Input panel

D. An Innovative HMI for an Optimal Cascade Hydropower System Operation

A HMI display (Figure 6) is based on a close collaboration between Mathematical Programming, MATLAB and LabVIEW. The result is a an operating environment that is streamlined and simplified, allowing operators to quickly determine the rules of water release along with the on/off sequencing of power generating units at three plants. The core of the decision system is based on (MILP) model, its aims to minimize power deficit while prioritize critical hydraulic and electrical constraints such as: reservoir water balance equations, reservoir storage, discharge rate, water discharge rate ramp, turbine-generator limit, generator unit ramp rate limit and minimum uptime/downtime of the units. A wise commitment schedule and proper power outputs level of hydropower units can decrease power deficit significantly, and simultaneously increase the safety and reliability of the power system.

Hourly operations of hydropower reservoirs often involve sudden changes in releases associated with the hourly fluctuations due to highly variable power demand. This automated solution provides the operator with an optimal daily operation at an hourly steps. The design focuses on details concerning awareness of the time delay between the consecutive reservoirs and their water storage and thus improving support for decision making. The HMI display provides operators with an optimal plan and better information visualization concerning power deficit and the water storage at the three reservoirs: Qaraoun, Anan and Joun. The application presents the information they need, when they need it and in a way that makes sense to them. This has a direct positive impact on the effectiveness and productivity of operators working within the hydropower plants.

With the HMI concept, the operator can see also the on/off sequencing of power generating units with the released water into every turbine over the whole planning day. In that context, effective power production among the units allows to ramp up and down hydropower generation during load transition in a smooth and flexible way.

III. Simulations and Discussions

In order to evaluate the benefits of coordinated hourly operation provided by the (STHGS) tool, several inputs need to be considered: 1- a load profile over 24-hours (Figure 7). 2- some technical information about the generators and turbines. 3- details about water inflow to every lake, storage capacity and dead storage (Table III) . 4- irrigation water share or cut.

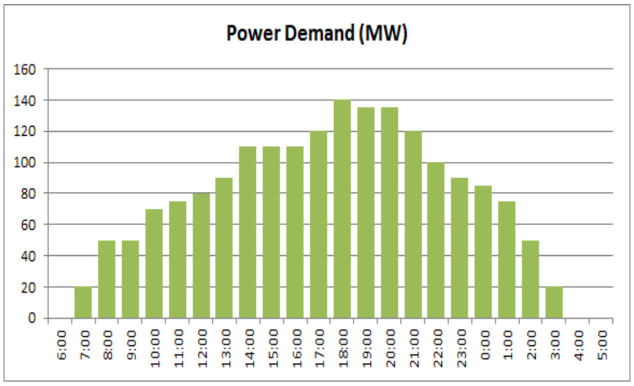


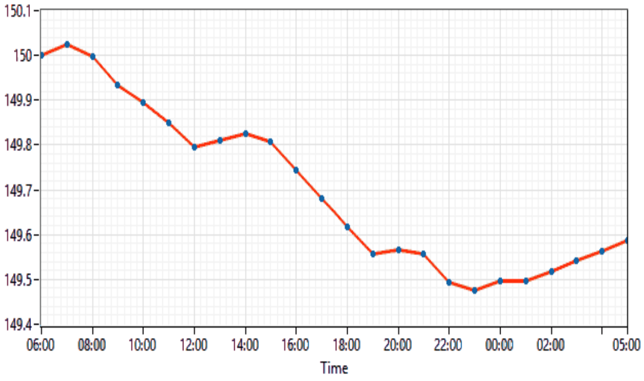
Fig. 7. Load Profile over 24 hours

TABLE III. Reservoir storage and water inflow

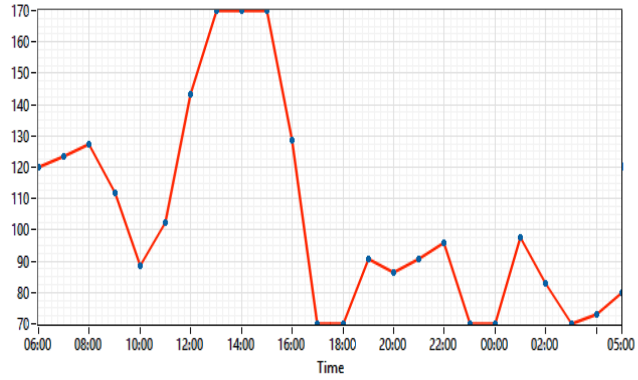
Lake	Initial Storage (MCM)	Dead Storage (MCM)	Water inflow (m$\hat{3}$/s)
Qaraoun	150	40	6.5
Anan	0.12	0.07	1
Joun	0.12	0.02	0.5

Once all relevant inputs are entered (Figure 6), the simulation is launched and, within 30 seconds the results are displayed on the output panel using an Intel Core i7-5500U CPU @ 2.40 GHZ, 12.0 GB RAM.

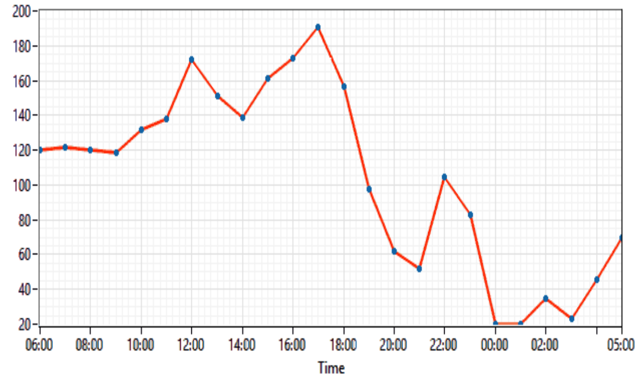
The daily hydropower generation is expected to follow the pattern of load demand at every hour. The water available for the entire day is allocated for generation in a way to fit energy demanded by EDL as much as possible. Starting with an initial storage equal to 150 millions of cubic meter in Qaraoun lake and a maximum allowed release of 950,000 cubic meters, a simulation is suggested by the (STHGS) tool showing power deficit at every hour. As a result of this coordinated operation, (Figure 8) shows that the water volume in the three reservoirs has stayed within the limits set by the operator to avoid critical water levels. In fact, the (STHGS) tool had accounted the storage constraints very well.



(a) Qaraoun Reservoir



(b) Anan Pond



(c) Joun Pond

Fig. 8. The storage of the three reservoirs over the 24 hours planning horizon

Further, fitting the energy demand did not just exhaust 950,000 m^3, but the system had to release an extra 126,000 m^3 from Anan lake and 93,000 m^3 from Joun pond to minimize power deficit. Since only a fixed amount of water is available to be released from Qaraoun dam for the day, the consequence is shortage in power production at 12:00 and 23:00 (Figure 9). Whereas, the generated power is distributed among units according to pattern in (Table IV). The application of (STHGS) makes full use of two extra water source Ain Zarqa spring and Bisri River (Figure 3) as a compensation of water shortage and benefits of the hydraulic head among cascade hydro plants. To obtain a perfect power fit, one of the following two solutions could be adopted: Either by

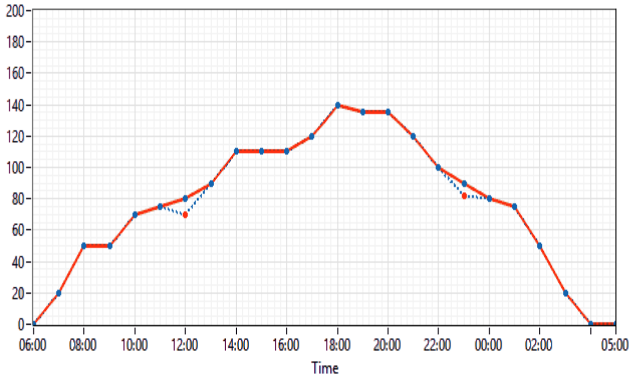


Fig. 9. Power deficit: Power demand (red) verses power supply (blue)

TABLE IV. LOAD DISTRIBUTION (IN MW) AMONG POWER GENERATION UNITS

Time	Markaba		Awali			Charles Helou	
	unit-1	unit-2	unit-1	unit-2	unit-3	unit-1	unit-2
6:00	0	0	0	0	0	0	0
7:00	9.19	9.19	0	0	0	1.62	0
8:00	16	16	0	16.39	0	1.62	0
9:00	11.63	11.63	0	23.49	0	1.62	1.62
10:00	12.66	12.66	0	34.54	0	5.066	5.066
11:00	14.45	14.45	0	21.43	21.43	1.62	1.62
12:00	1.333	1.333	0	0	34.54	16.2	16.2
13:00	1.6	1.6	31.4	0	31.4	0	24
14:00	7.826	7.826	23.74	23.74	23.74	0	23.13
15:00	16	16	15.2	15.2	15.2	16.2	16.2
16:00	16	16	20.57	20.57	20.57	8.15	8.15
17:00	16	16	13.34	13.34	13.34	24	24
18:00	15.7	15.7	20.2	20.2	20.2	24	24
19:00	2.366	2.366	27.42	27.42	27.42	24	24
20:00	6.201	6.201	24.87	24.87	24.87	24	24
21:00	16	16	24.14	24.14	24.14	7.8	7.8
22:00	7.511	7.511	12.33	12.33	12.33	24	24
23:00	0	1.333	10.78	10.78	10.78	24	24
0:00	0	8.196	18.1	18.1	18.1	8.75	8.75
1:00	0	1.333	17.13	17.13	17.13	11.13	11.13
2:00	0	0	5.867	5.867	5.867	16.2	16.2
3:00	0	0	0	10	10	0	0
4:00	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0

1) Increasing the maximum water release by 10,000 m^3, that is from 950,000 to 960,000 m^3, or
2) Sometimes by reducing the final storage at Anan and Joun

In a word, increasing the benefits of cascade hydro plants, this prototype tool will be extended by an appropriate river flow forecasting module with a planning capabilities up to 7 days ahead at hourly steps. This option will reduce the faults committed by human operators and the risk of flood, giving a wider insight about operational planning. In comparison with the present plan adopted by the operators of Markaba-Awali -Charles Helou plants, this intelligent tool will demonstrate more accuracy and superiority.

IV. CONCLUSION

The primary objective of the provided interface was seeking an hourly optimal operational power scheduling upto one day ahead by proper start and stop sequencing of power generating units at three plant: Markaba, Awali and Charles Helou along Litani River. This tool will give a complete insight of the water flow rate through every turbine with the power production aside with the availability of water in three reservoirs: Qaraoun, Anan and Joun during the whole planning period.

For full operation and control of the cascade plants, the Human Machine Interface (HMI) with its extended capabilities (upto 7 days ahead) will be linked to a SCADA system for remote monitoring and control. It will efficiently reduce the faults committed by human operators through centralizing the whole process by a fully automated system.

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