OPTIMAL OPERATION OF THERMAL UNITS USING PV/WIND ENERGY AND PUMPED HYDRO STORAGE GENERATION SYSTEM

Tahirou H. ISSOUFOU [1,*] Harun O. R. HOWLADER[1] Mohammed E. LOTFY[1] Agada I. Nkechi Charles KOMBOIGO Atsushi YONA Tomonobu SENJYU

[1] Department of Electrical and Electronics Engineering, University of the Ryukyus, Okinawa 903-0213, Japan.

* Tel: +81 80 9566 1657, Email address: thissoufou@gmail.com

Abstract: *The aim of this paper is to propose a methodology for solving generation planning problem for thermal units integrated with solar, wind power systems and Pumped Hydro Energy System in Niamey (capital of Niger) city power grid. The Renewable Energy Sources (RESs) are included in this model due to their free and available sources, positive effect on environment, and their contribution in reducing the cost of running the thermal units. The system comprises of conventional sources (eight thermal units), Photovoltaic (PV) system, Wind-Turbine Generators (WTGs) and Pumped Hydro Storage (PHS) as power sources for ensuring the availability of the energy needed by the customers. The generation planning known as Unit Commitment (UC) is solved using Mixed-Integer Linear Programming (MILP). This optimization technique considered here, is utilized to minimize the operational costs which include the fuel cost and the Start Up Cost (SUC) of the thermal units, shut-down cost of each thermal unit is taken as zero. The simulation results obtained using MATLAB environment, reveal the effectiveness and robustness of the proposed scheme.*

Key words*:* *Unit commitment (UC), Photovoltaic (PV) system, Wind-Turbine Generators (WTGs), Pumped Hydro Storage (PHS), Mixed-Integer Linear Programming* (MILP).

1. Introduction

In general, most of the electricity generation is based on the conventional energy resources to meet consumers' load demand. Nevertheless, the economical charge becomes bigger and bigger because of the high fuel cost and storage cost of the thermal units. Additionally, operation cost is also very expensive because the output of thermal units changes according to constantly changing power demand. For these reasons, the electrical power system operators found ways and means to operate the units in an optimal manner among which there is Unit Commitment (UC). The UC problem refers to the task of finding an optimal schedule, and a production level, for each generating unit over a given period of time. The unit commitment decision indicates which generating units are to be in use at each point in time over a scheduling horizon. This problem becomes a multistage program with 0/1 variables [1]. The UC problem has been widely discussed in the literature [2]. [3] firstly provides a literature survey of UC concept, objectives and constraints. Different UC models developed for addressing RESs impact are also reviewed. A fuzzy-optimization approach for solving the generation scheduling problem with consideration of wind and solar energy systems is presented in [4]. The use of the conventional sources like uranium, oil, coal, gas, etc through the burning process to generate electricity leads to the release of the greenhouse gases which leads to global warming. These conventional sources also tend to a depletion which causes a raise in the cost of electricity.

To prevent the future generations from the environmental pollution and to avoid the raise in cost of the electricity supplied, it is advised to accommodate the non-conventional energy sources like solar energy, wind energy, and several other forms of naturally available energies. [5] highlights the advanced research and development facilities located at the National Renewable Energy Laboratory that focus on energy systems integration designed to help national laboratories, academia, and industry conduct state-of-the-art research on the development and deployment of advanced energy components and systems. The use of hybrid energy systems, incorporating PV and wind resources can overcome or at least limit some of the problems associated with thermal generating unit only systems. The use of these renewable energy-based systems could help reduce the operating cost through the reduction in fuel consumption, increase system efficiency, reduce noise and emissions [6]. Availability and inexhaustibility of solar radiation and wind resulted in consideration of wind power and PV as the most preferred renewable energy sources [7]. Present researches of hybrid power generation systems focus mainly on the combination of photovoltaic (PV) arrays and wind turbines [8, 9], and the best compromise point between system power reliability and system cost is rarely considered in their design.

Solar PV array system and wind turbines are therefore receiving significant importance in recent researches and studies due to the lower electricity generation price after installing and positive effect on environment. However, they are also intermittent; therefore, in power generation systems employing wind and solar PV resources, there exists the need to account for the deficiencies and limitations which arise because of such intermittency in the energy supply capacity of such systems. Thus, there comes the need to make these systems more reliable and manageable in terms of their electrical energy generation and supply capacities. One solution to this need is the appropriate use of energy storage to ensure the system stability and economy. Many electrical storage systems like batteries, electric vehicles, compressed air energy storage, flywheel energy storage, pumped water storage etc., are used for improving reliability and reducing operating cost of power system. Among all these energy storage devices, Pumped Hydro Storage (PHS) which reacts when there is load peak, is the largest-capacity form of grid energy storage available which accounts for more than 99% of bulk storage capacity worldwide. The PHS is the most widespread energy storage technology with its first application in the 1890s [10] and a roundtrip efficiency of 70-85% [11]. It remains the most widely used and commercially viable electricity storage technology, especially for large energy storage systems of utility grids. This technology is now widely deployed in Western Europe, USA and Japan [12], which is more relevant to renewables integration. George's study [13] shows that wind energy with PHS is considered as the most suitable storage technology for allowing high wind penetration levels. [14] presents a method of optimal sizing of standalone hybrid wind-PV and pumped hydro energy storage system driven by not only the performance evaluation but also reliability and cost. Coordination and performance analysis of hybrid system consists of solar, wind and Pumped Hydro Storage Systems (PHSS) is described in [15]. PHS unit not only has the functions of peak-load regulation and frequency modulation, but also has the capability of fast response and excellent load tracking, which can effectively reduce the installed capacity of thermal power, decrease peak-load regulation depth, improve operational efficiency of the power system [16].

This paper proposes an optimal operation of the thermal units with introduction of PV, WTGs and PHS generation system to meet consumers' need of Niamey city (Niger). The objective function is the minimization of the operational cost which consists of the DGs fuel cost and SUC. In this paper, MILP is used as optimization technique to optimize the DGs with consideration of PV, WTGs and PHS as power source. The effectiveness of the proposed method is confirmed by tests results on MATLAB®.

2. Proposed power system configuration

The proposed power system configuration is depicted in Fig. 1. It consists of eight (8) TGUs, here referred to as Diesel Generators (DGs) which form the existing grid. PV, WTGs are introduced into the system in order to achieve the generation planning (UC). Due to the uncertainty and intermittence of these renewable energy sources, storage systems like PHS is also included into the system under study to cover the load demand fluctuations. Five (5) PHSs are introduced into the combined grid system and hybrid PV array system and WTGs.

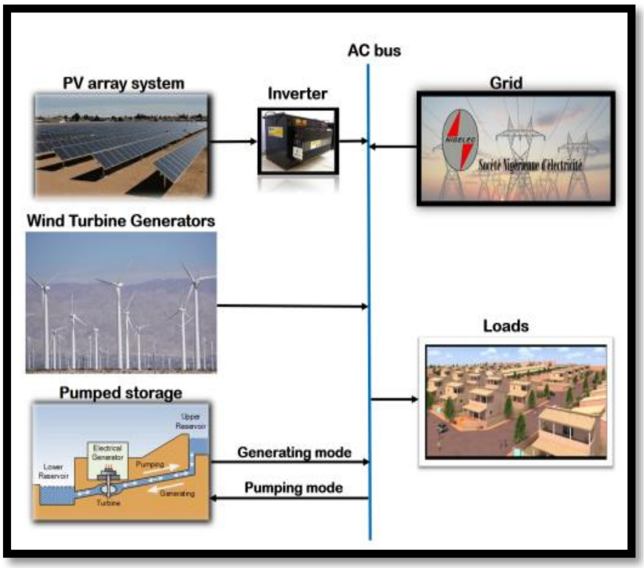

Fig. 1. Power system model.

3. System modeling

The three subsystems which are PV array, wind turbine generators, and pumped hydro storage supposed to be connected to the existing grid, are modeled as follows:

3.1 Modeling of PV array

The power (kW) supplied by a set of PV panels at time *t* is as follows [17]:

$$P_{PV}(t) = \eta_{PV}.A_{PV}.S(t) \tag{1}$$

Where, η_{PV} represents PV panels efficiency, A_{PV} (m^2) the total area occupied by PV panels, and *S(t)* (kW/m^2) the hourly solar radiation.

3.2 Modeling of wind turbine generator

The wind power generation is calculated from a conditional quadratic function of forecasted wind speed and several wind turbine related speed such as cut in/out and rated speed. The following equations are used for the calculation [18]:

$$P_{WTG}(t) = \begin{cases} 0 & : v_W(t) \leq v_1 \; or \\ & \;\; v_W(t) \geq v_3 \\ \psi(v_W(t)) & : v_1 \leq v_W(t) \leq v_2 \\ P_{Wn} & : v_2 \leq v_w(t) \leq v_3 \end{cases} \tag{2}$$

where $v_W(t)$ is forecasted wind speed at hour *t*; v_1, v_2 and v_3 are cut-in, rated and cut-out wind turbine speed; $\psi(v_W(t))$ is wind to energy conversion function and P_{Wn} is equivalent rated power output for wind power generation. $\psi\big(v_W(t)\big)$is approximated as a quadratic equation by assuming $P_{WTG}(t)$ varies as $v_W(t)$ between cut-in and rated wind speed [19]. $\psi(v_W(t))$ is expressed by the following equation

$$\psi\big(v_W(t)\big) = j_0 + j_1 v_W(t) \tag{3}$$

$$j_0 = \frac{P_{Wn} v_1^2}{v_1^2 - v_2^2}$$

$$j_1 = \frac{P_{Wn}}{v_2^2 - v_1^2}$$

3.3 Modeling of pumped hydro storage

The PHS subsystem consists of a turbine/generator unit and a pump/motor unit. The volume of the Upper Reservoir (UR) and the height difference between the upper and lower reservoir are the most important two variables which are observed in literature [20]. Fig. 2 shows the principle of operation of a pumped-storage power plant. In this paper, the height difference is fixed at 60m, and the Niger river is considered as the lower reservoir.

3.3.1 Generating mode: turbine/generator unit

During energy deficit periods, the output from the turbine/generator unit is [21, 22]:

$$P_t(t) = \eta_t.\rho.g.h.q_t(t) = c_t.q_t(t) \tag{4}$$

Where, η_t is the overall efficiency of the turbine/generator unit; ρ is the water density (=1000 kg g kg/m^3); g the gravitational acceleration (=9.81 m/s^2); h (m) is the elevating height; $q_t(t)$ (m^3/s) is the water volumetric flow rate input into the turbine at time t and c_t (kWh/m^3) the turbine generating coefficient. In this paper, $P_t(t)$ can also be called as $P_g(t)$ (output power of PHS during the generating mode).

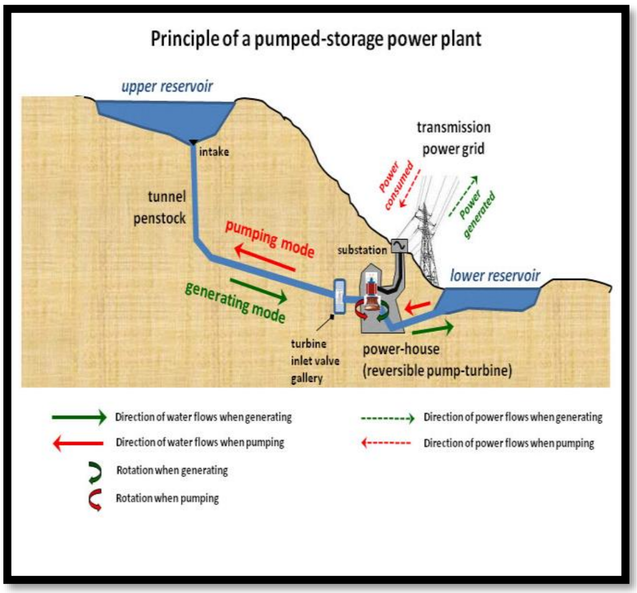

Fig. 2. Principle of operation of a pumped hydro storage power plant.

3.3.2 Pumping mode: pump/motor unit

The water flow rate elevated from the lower reservoir by the pumps is expressed in Eq. (5). The power source in the pumps is directly supplied by the hybrid grid and renewable energy sources. The water pumping can be compared to the charging rate of battery bank [21, 22].

$$q_p(t) = \frac{\eta_p . P_p(t)}{\rho . g . h} = c_p . P_p(t) \quad (5)$$

where, η_p is the overall pumping efficiency; $P_p(t)$ is the input power from the hybrid grid and RESs power generators to the pump at time t and c_p (m^3/kWh) is the water pumping coefficient.

3.3.3 Pump upper reservoir (UR)

The water quantity stored in the UR should be enough to meet the power demand of the system during peak load demand and insufficient hybrid energy generators. The quantity of water stored in the UR at any time *t* is determined by [21, 22]:

$$V_{UR}(t) = V_{UR}(t-1)(1-\alpha) + q_p(t) - q_t(t) \quad (6)$$

Where, α is the evaporation and leakage loss. α is similar to the self-discharge of battery bank and it is neglected for simplifying the calculations. The water level in the UR can be considered as the state of charge (SOC) of the storage tank.

$$SOC(t) = \frac{V_{UR}(t)}{V_{URmax}} \quad (7)$$

where, V_{URmax} is the maximum water quantity stored in the UR.

4. Formulation

In this section, objective function is formulated, system constraints are expressed, and optimization technique is described.

4.1 Objective function

The objective function in this paper is to minimize the Operational cost (OC) which includes fuel cost and SUC of the thermal units. This type of objective is referred to as the main objective of UC. Having eight thermal units and since UC is done for 24 hours so overall objective function is given by:

$$Min\ OC = \sum_{j=1}^{24}\sum_{i=1}^{8} U_{ij}F_i(P_{ij}) + U_{ij}(1 - U_{ij-1})S_i \quad (8)$$

Where, U_{ij} the ON ("1")/OFF ("0") status of unit *i* at *j* hour, F_i the fuel cost of unit *i*, P_{ij} the output power of i^{th} unit for j^{th} hour, S_i the Start-up cost of unit *i*.
Generally, the running cost of thermal unit is a function of output power of the particular unit and is given by [23]:

$$F_i(P_{ij}) = a_i + b_i P_{ij} + c_i P_{ij}^2 \quad (9)$$

Where, a_i, b_i, and c_i, are the fuel cost coefficients.
The DG (thermal unit) start up cost depends on the time the unit has been off prior to start up. The time dependent start up cost is given by [23]

$$S_i = S_{01} + S_{1i}(1 - e^{-T/t}) \quad (10)$$

In this paper shut down cost of each thermal unit is taken as zero.

4.2 System constraints

(i) System power balance:

The sum of output power of DGs, RESs (PV, and WTGs) output power, generating/pumping power of PHS must satisfy the load demand at every hour:

Generating mode operation

$$\sum_{j=1}^{24}\sum_{i=1}^{8} U_{ij}P_{ij} + P_{PV}(j) + P_{WTGs}(j) + P_t(j) = P_D(j) \quad (11)$$

Pumping mode operation

$$\sum_{j=1}^{24}\sum_{i=1}^{8} U_{ij}P_{ij} + P_{PV}(j) + P_{WTGs}(j) - P_p(j) = P_D(j) \quad (12)$$

where, $\boldsymbol{P_D(j)}$ is the total load demand for hour *j*.

(ii) Thermal unit output power limitation:

$$P_{i\,min} \le P_{ij} \le P_{i\,max} \quad (13)$$

Where, $P_{i\,min}$, and $P_{i\,max}$ are the minimum and maximum output power of thermal generating unit *i*, respectively.

(iii) Thermal unit minimum up and down time limitation:

$$ub_{ij} \le ub_{ij} \Rightarrow j \quad (14)$$

Where, $ub_{ij} \Rightarrow j$ is the continuous running time which has to be greater than start-up time $\left(ub_{ij}\right)$.

$$lb_{ij} \leq lb_{ij} \Rightarrow j \tag{15}$$

Where, $lb_{ij} \Rightarrow j$ is the continuous stopping time which has to be greater than shut down time $\left(lb_{ij}\right)$.

(iv) Pumped storage constraints:

a. Generation limit constraints:

$$P_{g\,min,\ k} \leq P_{g,\ k,\ j} \leq P_{g\,max,\ k} \tag{16}$$

$$P_{p\,min,\ k} \leq P_{p,\ k,\ j} \leq P_{p\,max,\ k} \tag{17}$$

Where, $P_{g\,min,\ k}$ and $P_{g\,max,\ k}$ are the minimum and maximum output power from the pump k during the generating mode for j^{th} hour respectively. $P_{p\,min,\ k}$ and $P_{p\,max,\ k}$ the minimum and maximum output power consumed by the pump k during the pumping mode for j^{th} hour respectively.

b. Water flow limit constraints:

$$Q_{g\,min,\ k} \leq Q_{g,\ k,\ j} \leq Q_{g\,max,\ k} \tag{18}$$

$$Q_{p\,min,\ k} \leq Q_{p,\ k,\ j} \leq Q_{p\,max,\ k} \tag{19}$$

Where, $Q_{g\,min,\ k}$ and $Q_{g\,max,\ k}$ are the minimum and maximum water flow rates in pump k during the generating mode for j^{th} hour respectively. $Q_{p\,min,\ k}$ and $Q_{p\,max,\ k}$ the minimum and maximum water flow rates in pump k during the pumping mode for j^{th} hour respectively.

c. Upper level limit of a reservoir:

$$V_{ur\,min,\ k} \leq V_{ur,\ k,\ j} \leq V_{ur\,max,\ k} \tag{20}$$

Where, $V_{ur\,min,\ k}$ and $V_{ur\,max,\ k}$ are the minimum and maximum water volume (m^3) that should be in the upper reservoir for j^{th} hour respectively.

d. Water balance between the upper and lower *reservoir:*

$$V_{ur,\ k,\ j+1} = V_{ur,\ k,\ j} - Q_{k,\ j} \tag{21}$$

$$V_{lr,\ k,\ j+1} = V_{lr,\ k,\ j} + Q_{k,\ j} \tag{22}$$

4.3 Optimization technique

The optimization technique used here is Mixed-Integer Linear programming (MILP) which is described as follows:

A Mixed-Integer Linear Programming (MILP) algorithm [24] is a solver for discrete optimization problems which uses many techniques to find the optimal solution from the objective function, $f^{T} x$, where f is a linear function vector which its elements are constant, and x is the solution vector. Bounds and linear constraints are the condition of the MILP but it has no nonlinear constraints. In particular, there are restrictions on the variables x to be the integer. For a given objective function f, inequality matrices A_{ineq} and equality matrices A_{eq} , inequality vector b_{ineq} and equality vector b_{eq} , lower-bound l_b and upper-bound u_b and the integer constraint *'intcon'*, the problem model for finding a solution vector x from the feasible solution space is shown in Eq. (23).

$$\min_{x} f^{T} x$$

$$subject\ to \begin{cases} x\ (intcon)\ are\ integers \\ A_{ineq}.x \leq b_{ineq} \\ A_{eq}.x = b_{eq} \\ l_b \leq x \leq u_b \end{cases} \tag{23}$$

The algorithm *intlinprog* uses 6 strategies to solve MILP and find the solution in any of the step. If it can find the solution in a step, *intlinprog* does not precede to the later step. The basic 6 strategies are shown as following [24]:

- Reduce the problem size using linear program preprocessing;
- Solve an initial relaxed (non-integer) problem using linear programming;
- Perform mixed-integer program preprocessing to tighten the LP relaxation of the mixed-integer problem;
- Try to use cutting-plane method to further tighten the LP relaxation of the mixed-integer problem;
- Try to find integer-feasible solutions using heuristics;
- Use a branch and bound algorithm to search systematically for the optimum solution.

5. Test results and discussions

The MILP optimization technique is applied to get the optimal values of the decision variables which make the objective function to be achieved that is minimization.

5.1 Simulation data

Table 1 shows the parameters of each DG. The parameters of PHSs are described in Table 2. PV array system with a maximum output power of 21.8 MW and the WTGs 49 MW as maximum output power are represented by Fig. 3 and 4 respectively.

Table 1: Parameters of each diesel generator

DG units	DG1~4	DG5&6	DG7
P_{DGi}^{max} [MW]	25	19	9
P_{DGi}^{min} [MW]	5	4	2
ub_{ij}	1	1	1
lb_{ij}	1	1	1
a_i [$]	150	150	150
b_i [$/MW]	30	30	30
c_i [$/MW]	0.000398	0.00079	0.00085
	0.00068	0.00020	
	0.00064		
	0.00083		
SUC_i [$]	180	120	90

DG units	DG8
P_{DGi}^{max} [MW]	2
P_{DGi}^{min} [MW]	0
ub_{ij}	1
lb_{ij}	1
a_i [$]	150
b_i [$/MW]	30
c_i [$/MW]	0.00098
SUC_i [$]	180

Table 2: Parameters of pumped hydro storage

PHS units	PHS1~5
P_{PHSi}^{max} [MW]	10
E_{PHSi}^{max} [MWh]	86.4
V_{ur} [m^3]	317,064.44
V_{lr} [m^3]	Niger river
h [m]	60
g [m/s^2]	9.81
ρ [kg/m^3]	1000
$\eta_{turbine}$ [%]	90
η_{pump} [%]	90

5.2 Discussions

The daily load profile and the shifted load 1 are depicted in Fig. 5. Here, the load has been levelized after introducing PV and WTGs power. The PHS system works like battery which means it also has state of charge. The PHS's SOC is shown in Fig. 6 where the maximum charge is set to 80% and the minimum discharge to 20%. The generating and pumping power are shown in Fig. 7. As it can be seen from this Fig. 7, the positive bars indicate the generating (discharging) operation of the pumps. This case happens when the total load cannot be met by the total generated power when considering the priority of having UC, then PHSs reacts by suppling the required power needed by the generation side to cover the consumers' load demand. During off-peak load demand, PHSs absorb active power from the combined grid system (8 DGs) and hybrid PV array system and WTGs. This is shown by the negative bars in Fig. 7 which indicate the pumping (charging) operation of the pumps.

Moreover, Fig. 8 represents the UC for proposed method with levelized load 1 and levelized load 2. Here, we can notice that the load profile (load demand) has been shifted a little bit, which is the levelized load 1. This results from the contribution of PV and WTGs. Because of the unpredicted output power of these renewable energies, leveling the load demand is only achieved by using energy storage systems like in this paper PHS. Thus, the load demand has been completely shifted. This is to say that leveling the load demand is obtained through the incorporation of PHSs. On the other hand, UC is also achieved as it can be observed that the units are committed and decommited depending on their costs and loads. This turning ON/OFF status brings us to the result of thermal units' operational cost reduction as well as CO_2 reduction. As this technique keeps holding, we can say that the fuel cost and SUC which form the objective function got minimized.

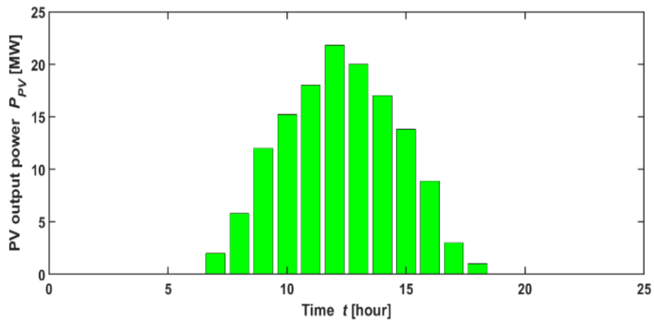

Fig. 3. PV output power.

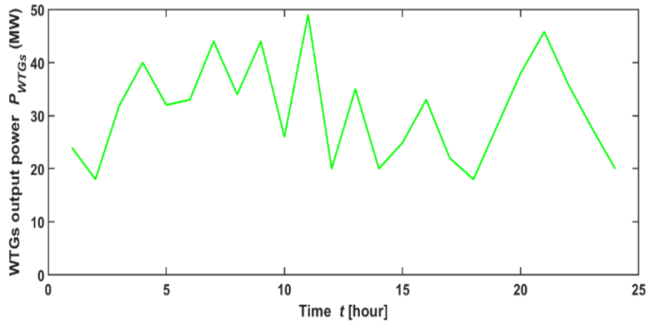

Fig. 4. WGTs output power.

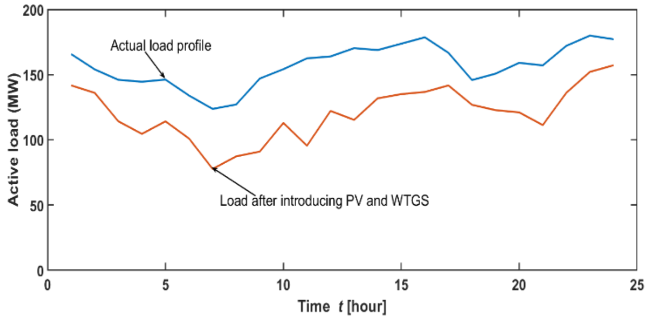

Fig. 5. Active load (load demand and load after PV and WTGs penetration).

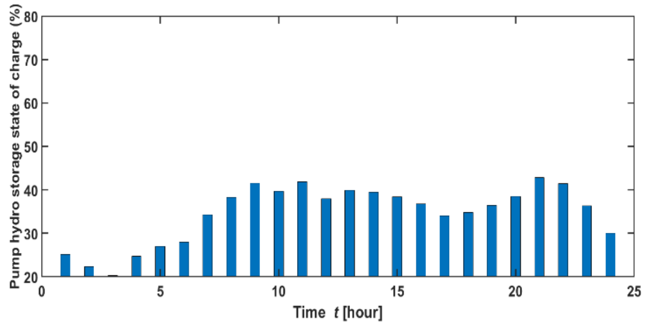

Fig. 6. PHS state of charge

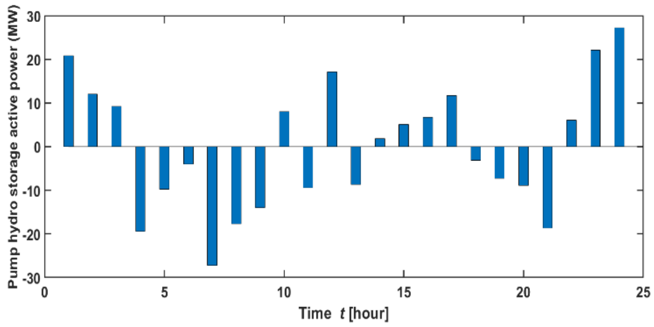

Fig. 7. PHS generating/pumping output/input power

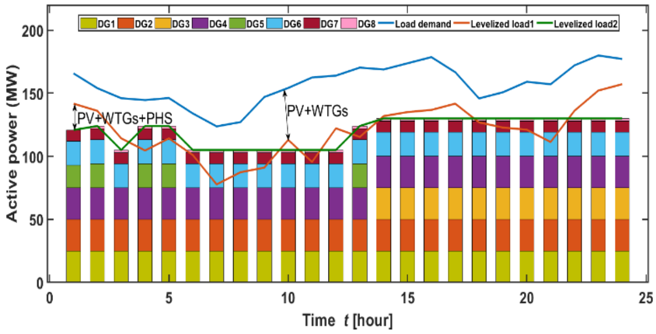

Fig. 8. UC for proposed method

6. Conclusion

This paper has described the generation planning of eight units which consist the existing grid system of Niamey city. The methodology used in this paper is incorporated renewable energies and pumped hydro storage in the thermal unit commitment. Test results shown that the use of PV, WTGs and PHS can considerably reduce the operational cost of the thermal units while balancing the power generation plant side and the power demand side. Simulation results also revealed that the leveling of load demand can only be done by the PHS. The MILP was used to obtain the best values for decision variables in order to minimize the objective function subjected to system and unit constraints.

References

1. Samer T., John R.B., Erik L.: *A Stochastic Model for the Unit Commitment Problem*, IEEE Transactions on Power Systems, Vol. 11, no. 3, 1996, p. 1497-1508.
2. Abujarad S.Y.I., Mustafa M.W., Jamian J.J.: *Unit Commitment Problem Solution in The Presence of Solar and Wind Power Integration by an Improved Priority List Method*, 6th International Conference on Intelligent and Advanced Systems (ICIAS), August 15-17, 2016, Kuala Lumpur, Malaysia.
3. Abujarad S.Y.I., Mustafa M.W., and Jamian J.J.: *Recent Approaches of Unit Commitment in the Presence of Intermittent Renewable energy Resources: A Review*, Renewable and Sustainable Energy Reviews, Vol. 70, 2017, p. 215-223.
4. Ruey-Hsun L., Jian-Hao L.: *A Fuzzy-Optimization Approach for Generation Scheduling with Wind and Solar Energy Systems*, IEEE Transactions on Power Systems, Vol. 22, no. 4, 2007, p. 1665-1674.

5. Kroposki B., Mooney D., Markel T., Lundstrom B.: *Energy Systems Integration Facilities at the National Renewable Energy Laboratory*, National Renewable Energy Laboratory, 2012, Colorado, USA.
6. Wies, R. W., Johnson R.A., Agrawal A.N., Chubb T.J.: *Simulink Model for Economic Analysis and Environmental Impacts of a PV with Diesel-Battery System for Remote Villages*, IEEE Transactions on Power Systems, Vol. 20 no. 2, 2005, p. 692-700.
7. Deshmukh M.K., Deshmukh S.S.: *Modeling of Hybrid Renewable Energy Systems*, Renewable and Sustainable Energy Reviews, Vol. 12 no.1, 2008, p. 235-249.
8. Tina G., Gagliano S., Raiti S.: *Hybrid Solar/Wind Power System Probabilistic Modeling for Long-Term Performance Assessment*, Solar Energy, Vol. 80, no. 5, 2006, p. 578-588.
9. Markvart T.: *Sizing of Hybrid PV-Wind Energy Systems*, Solar Energy, Vol. 59 no. 4, 1996, p. 277-281.
10. Kumari J.S., Babu C.S.: *Mathematical Modeling and Simulation of Photovoltaic Cell using Matlab-Simulink Environment*, International Journal of Electrical and Computer Engineering (IJECE), Vol. 2 no. 1, 2012, p. 26-34
11. Lindley D.: *The Energy Storage Problem*, Nature , Vol. 463, 2010, p. 18-20.
12. George B: *Feasibility Study of a Hybrid Wind/Hydro Power-System for Low Cost Electricity Production*, Applied Energy, Vol. 72, 2002, p. 599-608.
13. Caralis G.: *Hybrid Systems (Wind with Pumped Storage*), International Conference: RES & Energy Savings in Islands, local planning and European cooperation, October 23-25, Milos, Greece.
14. Solomon E., Ibrahim U., Alireza M.: *Optimal Sizing of Wind-PV-Pumped Hydro Energy Storage Systems*, 4th International Symposium on Environmental Friendly Energies and Applications (EFEA), September 14-16, 2016, Belgrade, Serbia.
15. Gangadharayya S., Neeraj K.S., Shilpa B.: *Coordination and Performance Analysis of Pumped Hydro Storage System Integrated with Solar, Wind Hybrid System*, International Conference of Energy, Communication, Data Analytics and Soft Computing (ICECDS-2017), August 1-2, 2017, Chennai, India.
16. Nan S., Suquan Z., Xunwen S., Rongfeng y., Xianhui Z.: *Unit Commitment and Multi-Objective Optimal Dispatch Model for Wind-hydro-thermal Power System with Pumped Storage*, IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), May 22-26, 2016, Hefei, China.
17. Mohammad M.S., Masahiro F., Mohammed E.L., Atsushi Y., Tomonobu S.: *Optimal Economical Sizing of Grid-Connected Hybrid Renewable Energy System*, Journal of Energy and Power Engineering, Vol. 11, 2017, p. 244-253.
18. Shantanu C., Tomonobu S., Ahmed Y.S., Atsushi Y., Toshihisa F.: *Optimal Thermal Unit Commitment Integrated with Renewable Energy Sources Using Advanced Particle Swarm Optimization*, IEEJ Transactions on Electrical and Electronic Engineering, Vol. 4, 2009, p. 609-617.
19. Powell W.R.: *An Analytical Expression for the Average Output Power of a Wind Machine*, Solar Energy Vol. 26 no. 1, 1981, p. 77-80.
20. Kousksou T., Bruel P., Jamil A., El Rhafiki T., Zeraouli Y.: *Energy Storage: Applications and Challenges*, Solar Energy Materials and Solar Cells, Vol. 120, Part A, 2014, p. 59-80.
21. Tao M., Hongxing Y., Lin L., Jinqing P.: *Pumped Storage-Based Standalone photovoltaic Power Generation System: Modeling and Techno Economic Optimization*, Applied Energy, Vol. 137, 2015, p. 649-659.
22. Tao M., Hongxing Y., Lin L., Jinqing P.: *Technical Feasibility Study on a Standalone Hydrid Solar-Wind System with Pumped Hydro Storage for a Remote in Hong Kong*, Renewable Energy, Vol. 69, 2014, p. 7-15.
23. Md. Sajid A., Matam S.K.: *Unit Commitment of Thermal Units in Integration with Wind and Solar Energy Considering Ancillary Service Management Using Priority List (IC) Based Genetic Algorithm*, International Conference on Innovation and Challenges in Cyber Security (ICICCS-INBUSH), February 3-5, 2016, Noida, India.
24. Punysia K., Udom J.: *A Comparative Study of Mixed-Integer Linear Programming and Genetic Algorithms for Solving Binary Problems*, 5th International Conference on Industrial Engineering and Applications, April 26-28, 2018, Singapore, Singapore.