Unit Commitment in the Presence of Renewable Energy Sources and Energy Storage System: Case Study

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Abstract: This paper presents a real approach for thermal unit commitment (UC) problem solution in Niamey (Niger). The proposed methodology consists of four conventional thermal generating units and imported power (IMP) from a neighboring country as the existing grid in addition to the inclusion of Photovoltaic (PV) power, Wind Turbine Generators (WTGs), and Battery Energy Storage System (BESS). Minimization of the total daily operating cost is considered as the objective function in two cases. In the first case, UC with thermal units considering the IMP, PV and BESS is described. In the second case, WTGs are introduced beside high penetration of PV and BESS and the IMP is removed in order to get rid of its economical and mostly political problems. MILP (Mixed-Integer Linear Programming) is used here as the optimization technique to obtain an optimal unit commitment problem solution with consideration of PV, WTGs and BESS. The effectiveness and robustness of the proposed scheme is verified by numerical simulations using MATLAB environment.

Key words: UC, PV, WTGs, BESS, MILP.

Nomenclature

UC	Unit Commitment
PV	Photo-Voltaic
WG	Wind Generation
BESS	Battery Energy Storage System
WTGs	Wind Turbine Generators
TGs	Thermal Generators
IMP	Imported Power
RESs	Renewable Energy Sources
SOC	State of Charge
DOD	Depth of Discharge
TDOC	Total Daily Operating Cost
TG	Thermal Generator
SUC	Start Up Cost
NTG	Number of Thermal Generators
NPV	Number of PV panels
NWTG	Number of Wind Turbine Generators
NBESS	Number of Battery Energy Storage System
MILP	Mixed-Integer Linear Programming

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1. Introduction

Niger is a landlocked continental West African country located south of the Sahara. It is surrounded in the north by Algeria and Libya, to the east by Chad, to the south by Nigeria and Benin, to the west by Burkina Faso, and northwest by Mali. It is the largest country in West Africa with an area of 1,267,000 square kilometers (km^2). Electrically, Niger is highly dependent on imports, covering more than 75% of its national electricity needs. Its power supply is ensured by 5 interconnection lines from Nigeria [1].

As aforementioned, Niger has to develop some ways of producing its own electrical energy to meet its population load demand.

Habitually, the electrical energy supplied to load demand is being generated by thermal generating units. Generally, the fuel cost for thermal units is expensive because of transportation cost, storage cost, and so on. However, power producers should use an optimal operation of thermal units for high efficiency, operational cost and carbon emission reductions. To achieve the above-mentioned points, UC must be

incorporated into the power system. UC is an operational planning. The purpose of this planning is to determine a schedule called Unit Commitment Schedule which tells us beforehand when and which units to start and shut down during the operation over a prespecified time, such that the total operating cost for that period becomes minimum [2]. The objective of the UC is to obtain the minimum cost without violating the system constraints, this cost includes the generators start-up cost (SUC), fuel cost and shut down cost [3]. Unit commitment of thermal power plant in integration with wind and solar plant using genetic algorithm is described in Ref. [4].

In addition, the use of conventional energy sources like coal, gas, oil through the burning process to generate electrical energy leads to the release of the greenhouse gases which in turn leads to global warming. To save the earth and future generations, power producers are accommodating recently the use of non-conventional energy sources like solar energy, wind energy and several other forms of naturally available energies. It is better to integrate them with the conventional energy sources to solve problems such as the mismatch between power generation and load demand, to secure the minimum total cost of the system, the global warning eradication, etc.

However, it is difficult to predict the power generated by the renewable resources such as PV and WG because they have certain intermittent and uncertainty. To suppress their intermittent, compensating their fluctuations by other generators is an efficient method to ensure the system stability and economy. Their inclusion into the power system brought major challenges as a result of their output variations. As countermeasures, the Battery Energy Storage System (BESS) is introduced into the power system under study. BESS is an effective system that can be used to supplement the power output variation of the renewable sources. It is required to solve the optimal capacity because it is costly [5-8]. BESS is developed to achieve longer usage time, and better efficiency,

which are very useful in electricity business. In fact, the introduced BESS increases the capital cost as well as overheads resulting from the maintenance due to the characteristic deterioration of the battery.

In this paper, an optimization approach is proposed to determine an optimal thermal unit commitment problem solution with the inclusion of PV, WTGs and BESS. Minimization of the total daily operating cost is considered here as the objective function. The proposed method uses MILP as optimization method to tune the values of decision variables in two cases as follows: In the first case, PV and BESS are integrated with the conventional power plant (four TGs and IMP) while as in the second case, IMP is discarded through more penetration of PV and WTGs to the four TGs. Also, BESS is considered. The effectiveness of the proposed method is confirmed by simulation results on MATLAB®.

2. Proposed Power System Description

Fig. 1 shows the power system configuration of Niamey (Capital city of Niger), comprising of the grid (imported power from Nigeria), four thermal generators (TG1, TG2, TG3, TG4) with the penetration of PV, WTGs, and BESS bank to meet the changing load demand, and Niamey power demand.

3. System Mathematical Modeling

PV array, wind turbine generators, and the battery bank storage constitute the three subsystems which should be connected to the existing grid.
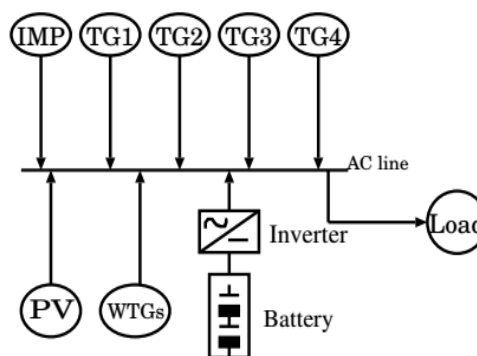

Fig. 1 Power system configuration.

3.1 PV Array Modeling

For a PV array having an efficiency η_{PV} and an area A_{PV}(m^2), the output power P_{PV} (kW), when subjected to the available solar insolation R (kW/m^2) on the titled surface, is given at hour t by Eq. (1) [9]:

$$P_{PV}(t) = R(t) . A_{PV} \cdot \eta_{PV} \qquad (1)$$

3.2 WTG Modeling

A WTG produces power P_{WTG} when the wind speed V is higher than the cut-in speed V_{ci} and is shut-down when V is higher than the cut-out speed V_{co}. When $V_r < V < V_{co}$ (V_r is the rated wind speed), the WTG produces rated power P_r at hour t. If $V_{ci} < V < V_r$, the WTG output power varies according to the cube law. This behavior is described by the following equations [10, 11].

$$P_{WTG}(t) = \begin{cases} P_r(t) . \left(\dfrac{V^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} \right), V_{ci} \leq V \leq V_r \\ P_r(t), V_r \leq V \leq V_{co} \\ 0, V_{co} \leq V \text{ or } V \leq V_{ci} \end{cases} \qquad (2)$$

where

$$P_r(t) = \frac{1}{2} \cdot C_p \cdot \rho_{air} \cdot A_w \cdot V_r^{\,3}(t) \qquad (3)$$

In the above equation, C_p, ρ_{air} (kg/m^3), and A_w (m^2) denote the power coefficient, air density, total swept area by the rotating turbine blades respectively. As it is seen, wind power is proportional to the cube of wind speed, so even modest increase in wind speed can affect the wind power. In order to get higher wind output, one way is to mount the turbine on a taller tower. Surface winds are getting slowed by high irregularities such as forests and buildings. The following equation is for the effect of roughness of the earth's surface on the wind speed [12]:

$$\frac{V}{V_0} = \left(\frac{h}{h_0} \right)^\alpha \qquad (4)$$

where, V and V_0 are the wind speeds at height h and h_0 respectively, and α is the roughness factor. The α value is less than 0.1 for flat land, water or ice and more than 0.25 for forested landscapes.

3.3 BESS Modeling

The amount of power generated by the grid, RESs at hour t is as follows:

$$P_G(t) = P_{grid}(t) + P_{RESs}(t) \qquad (5)$$

where P_{grid}(t), and P_{RESs} (t) are the power output from the grid and the renewable energy sources at time t respectively.

Two scenarios are considered in this study:

Scenario 1: The RESs used here are only PV and the grid which comprises of the four TGs and the IMP as follows:

$$P_{RESs}(t) = P_{PV}(t) \qquad (6)$$
$$P_{grid}(t) = P_{TGs}(t) + P_{IMP}(t) \qquad (7)$$

Scenario 2: Beside PV, WTGs are used, and the IMP is removed from the grid as follows:

$$P_{RESs}(t) = P_{PV}(t) + P_{WTGs}(t) \qquad (8)$$
$$P_{grid}(t) = P_{TGs}(t) \qquad (9)$$

where, P_{PV} (t), P_{TGs} (t), P_{IMP} (t), and P_{WTGs} (t) are the power output from the PV array system, the four thermal generators, the imported power and the wind turbine generators at time t respectively.

At any hour t, the state of charge of the battery [$SOC(t)$] is related to the previous state of charge [$SOC(t - 1)$] and to the energy production and consumption situation of the system during the time from $t - 1$ to t.

During the charging process, when the battery power P_B flows toward the battery (i.e., $P_B > 0$), the available battery state of charge at hour t can be described by Eq. (10) [13]:

$$SOC(t) = SOC(t - 1) + \left(\frac{P_B(t) \times \Delta t}{1000 \times C_b} \right) \qquad (10)$$

where, Δt is the simulation step time, and C_b is the total nominal capacity of the battery in kilowatt-hours. On the other hand, when the battery power flows outside the battery (i.e., $P_B < 0$), the battery is in discharging state. Therefore, the available battery state of charge at hour t can be expressed as [13]:

$$SOC(t) = SOC(t - 1) - \left(\frac{P_B(t) \times \Delta t}{1000 \times C_b} \right) \qquad (11)$$

To prolong the battery life, the battery should not be over discharged or overcharged. This means that the SOC at any hour t must be subjected to the following constraint [13]:

$$(1 - DOD_{max}) \leq SOC(t) \leq SOC_{max} \qquad (12)$$

where, DOD_{max} SOC_{max} are the battery's maximum permissible depth of discharge and SOC, respectively.

4. Formulation

In this section, objective function is formulated, restrictions are presented, and optimization technique is described.

4.1 Objective Function

Minimizing the total daily operating cost (TDOC) which consists of fuel cost and SUC, constitutes the objective function of this paper.

$$\min \quad TDOC = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{NTG} \left(F_{ci}(P_{TGi}(t)) \right. \right. \\ \left. \left. + SUC_i(TG_i(t)) \right) \right\} \qquad (13)$$

where, T, NTG, F_{ci}, $P_{TGi}(t)$, and $SUC_i(TG_i(t))$, are the total scheduling period [hours], total thermal generating units, fuel cost function [$] of unit i at hour t, output power of unit i at hour t and startup cost [$] of unit i at hour t of TGs, respectively.

The fuel costs F_{ci} are calculated by piecewise linear blocks quadratic equation [14].

$$F_{ci}(P_{TGi}(t)) = a_i + b_i P_{TGi}(t) + c_i P_{TGi}^2(t), \\ \forall i \in I, \forall t \in T \qquad (14)$$

4.2 Constraints

(i) Power balance constraint

The summation of each unit power output from the generating units, PV output power, WTGs output power, and discharging/charging power of BESS, should exactly satisfy the load demand for every hour. Thus, the system power balance equation at hour t can be expressed as:

Case 1

$$P_{IMP}(t) + \sum_{i=1}^{NTG} P_{TGi}(t) + \sum_{i=1}^{NPV} P_{PVi}(t) \\ + \sum_{i=1}^{NBESS} P_{BESSi}(t) \times \eta_b \qquad (15) \\ - \sum_{i=1}^{NBESS} P_{BESSi}(t) = P_{Ld}(t)$$

Case 2

$$\sum_{i=1}^{NTG} P_{TGi}(t) + \sum_{i=1}^{NPV} P_{PVi}(t) + \sum_{i=1}^{NWTG} P_{WTGi}(t) \\ + \sum_{i=1}^{NBESS} P_{BESSi}(t) \times \eta_b \qquad (16) \\ - \sum_{i=1}^{NBESS} P_{BESSi}(t) = P_{Ld}(t)$$

where, η_b and $P_{Ld}(t)$ are the battery efficiency and total load demand at hour t.

(ii) Minimum/maximum thermal unit output power constraint:

$$P_{TGi}^{min} \leq P_{TGi}(t) \leq P_{TGi}^{max} \qquad (17)$$

where, P_{TGi}^{min}, and P_{TGi}^{max} are the minimum and maximum output power of thermal generating unit i, respectively.

(iii) Thermal unit up and down time constraint:

$$ub_i(t) \leq ub_i(t) \Rightarrow (t) \qquad (18)$$

where, $ub_i(t) \Rightarrow (t)$ is continuous running time which has to be greater than start-up time $(ub_i(t))$.

$$lb_i(t) \leq lb_i(t) \Rightarrow (t) \qquad (19)$$

where, $lb_i(t) \Rightarrow (t)$ is continuous stopping time which has to be greater than shut down time $(lb_i(t))$.

(iv) BESS unit output power constraint:

$$P_{BESSi}^{min} \leq P_{BESSi}(t) \leq P_{BESSi}^{max} \qquad (20)$$

where, P_{BESSi}^{min}, and P_{BESSi}^{max} are the BESS's minimum and maximum output power of battery i, respectively.

(v) BESS unit state of operation limit constraint:

$$P_{BESSi}^{min}(= 10\%) \leq P_{BESSi}(t) \leq P_{BESSi}^{max}(= 90\%) \quad (21)$$

where, P_{BESSi}^{min}, and P_{BESSi}^{max} are the BESS's minimum and maximum percentage of state of operation of battery i, respectively.

4.3 Optimization Technique

A mixed-integer linear programming (MILP) algorithm [15] 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 in 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. (22).

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

$$subject\ to \begin{cases} x\ (intcon)\ are\ integers \\ A_{ineq}.x \le b_{ineq} \\ A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{cases} \quad (22)$$

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 [15]:

• 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. Simulation Results and Discussions

MILP has been used to obtain the optimal values of the decision variables for making the objective function to be minimized in two scenarios.

5.1 Scenario 1

The model components are the grid (IMP, TG1, TG2, TG3, and TG4), and future penetration of PV array system and BESS.

In some hours of the day, the grid cannot cover the load demand even though all the TGs are commited. However all the TGs should not be turned on at the same time and PV and BESS are introduced to the grid in order to achieve the objective function while covering the load demand. Fig. 2 describes the generated power by the PV array system. The SOC of the battery is shown in Fig. 3 and Fig. 4 indicates the battery bank charging/discharging power output where the battery bank stores the surplus power during off-peak load and delivers it in mismatch conditions. Moreover, Fig. 5 depicts the load demand leveling. Here, we can notice that the load has been shifted resulting from cutting the peak loads. This action
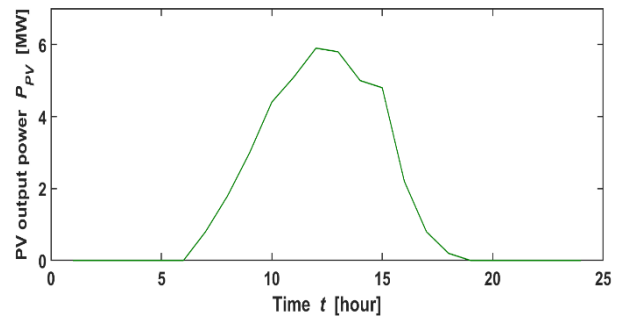

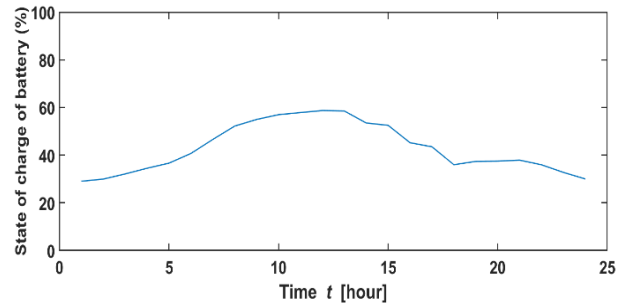Fig. 2　PV output power under scenario 1.
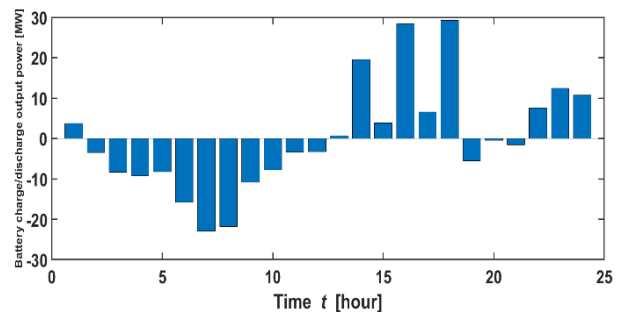

Fig. 3　Battery state of charge under scenario 1.

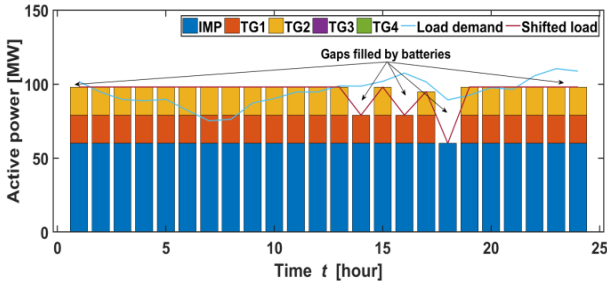Fig. 4　Battery charge\discharge output power under scenario 1.

Fig. 5   Optimal thermal UC for proposed method for scenario 1.

Fig. 6   PV output power under scenario 2.

comes from the contribution of using BESS which has an effective method for peak load shaving. The gaps shown are filled by the batteries output power. UC is achieved because we can observe that not all the four TGs are commited.

5.2 Scenario 2

In this scenario, PV array has been increased and WTGs are used to replace the IMP. The proposed approach is expected to be as long run plan to get independent of the IMP's political and economical problems. PV array output power and WTGs power output are illustrated by Figs. 6 and 7, respectively. Fig. 8 shows the battery state of charge. The battery bank charging\discharging output power is depicted in Fig. 9. During the peak load periods, the BESS releases active power to shave the peak load. However, the BESS absorbs the active power from the hybrid grid (only the 4 TGs) and the RESs (PV array and WTGs) during the valley periods. Finally, Fig. 10 represents the load profile leveling. This is achieved only by the use of BESS despite the fact that PV and WTGs are used. Here shifted load 1 designates the shifted load before using the BESS and shifted load 2, the one when BESS is introduced. On the other hand, the gap between the total load demand and the shifted load 1 is filled by the PV array power output and WTGs output power and all the gaps below the shifted load 1 are filled by the output power of the batteries. As it can be seen from Fig. 10 some TGs are decommited. This fact confirms that the objective function which is the total daily operating cost reduction consisting of fuel cost and SUC, has been achieved.
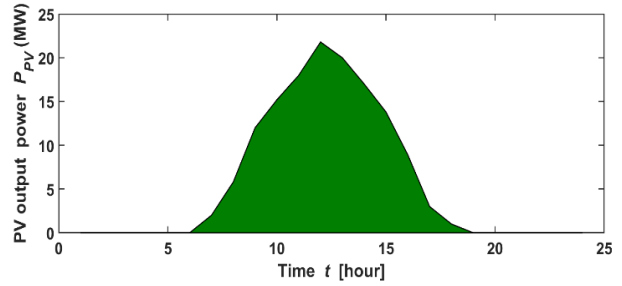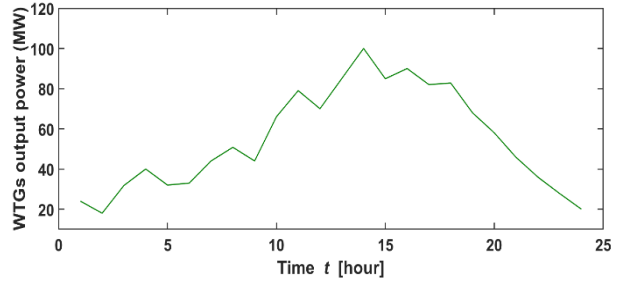

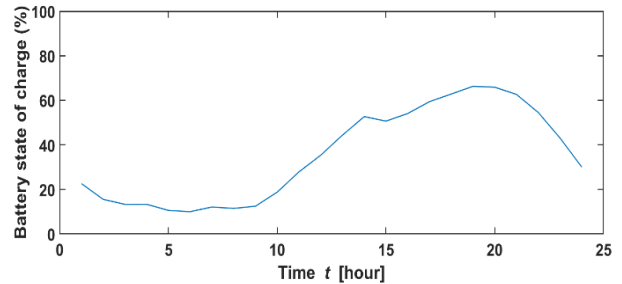**Fig. 7   WTGs output power under scenario 2.**

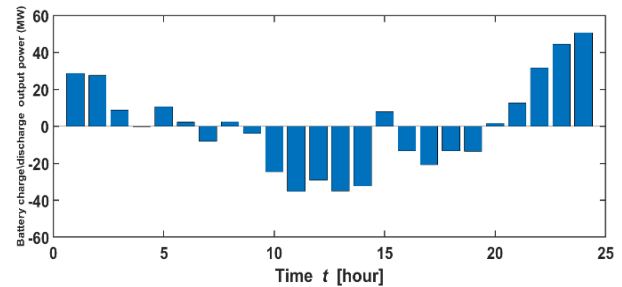**Fig. 8   Battery state of charge under scenario 2.**

Fig. 9   Battery charge\discharge output power under scenario 2.
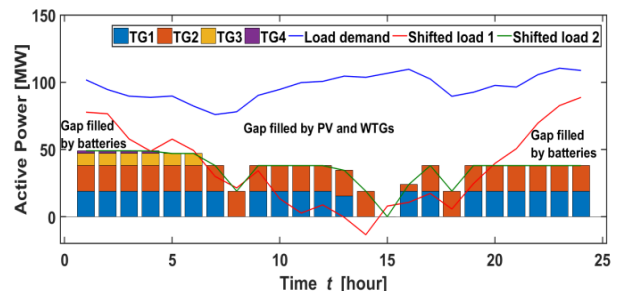

Fig. 10   Optimal thermal UC for proposed method for scenario 2.

6. Conclusion

This paper has presented an optimal thermal UC problem solution with the integration of RESs and BESS for the Niamey city power grid. The proposed power system is examined in two scenarios. In the scenario 1, the power system comprises of PV, and BESS connected to the grid, which in turn consists of IMP and four TGs. In the scenario 2, beside large penetration of PV array, WTGs are introduced and BESS, are all connected to the grid. Here the grid consists of only the four TGs, IMP has been removed because of its economical and political issues. MILP has been applied as optimization technique. The effectiveness and robustness of the proposed control methodology for meeting the load while minimizing the total daily operating cost, and solving the UC problem for the thermal generators over the day with the integration of PV, WTGs, and BESS is confirmed through the two scenarios using MATLAB environment.

References

[1] Salifou, G. 2015. "The Energy Sector of Niger: Perspectives and Opportunities." *Energy Charter Secretariat Knowledge Center*, 9-10.

[2] Ravi, C. 2017. "What Is a Unit Commitment in a Power System."

[3] Sarjiya, S., Arief, B. M., and Andi, S. 2015. "Unit Commitment Solution Using Genetic Algorithm Based on Priority List Approach." *Journal of Theoretical and Applied Information Technology* 72 (3): 394-403.

[4] Devendra, K., Ashiwani, K., and Lokesh, K. Y. 2014. "Unit Commitment of Thermal Power Plant in Integration with Wind and Solar Plant Using Genetic Algorithm." *International Journal of Engineering Research & Technology (IJERT)* 3 (7): 664-9.

[5] Kazuki, O., Shota, K., Michael, P., Atsushi, Y., and Tomonobu, S. 2013. "Optimal Operation Planning of Wind Farm Installed BESS Using Wind Power Forecast Data Wind Turbine Generators Considering Forecast Error." *International Journal of Emerging Electric Power Systems* 14 (3): 207-18.

[6] Shota, H., Wang, M., Atsushi, Y., Tomonobu, S., and Toshihisa, F. 2013. "Optimal Operation Method Considering Uncertainty of Renewable Energy and Load Demand in Micro-grids." In the 5th International Conference on Advanced Power System Automation and Protection, Jeju, Korea, October 28-31.

[7] Shota, H., Abdul Motin, H., Yuhei, S., Atsushi, Y., Tomonobu, S., and Toshihisa, F. 2014. "Optimal Operation Method Considering Replanning and Uncertainty in Power Systems." The International Conference on Electrical Engineering, Jeju, Korea, June 15-19.

[8] Shota, T., Ryuto, S., Aditya, S., and Tomonobu, S. 2016. "Optimal Operation Method with Fuel Cells in Plural Region Power Systems." In 2016 IEEE International Conference on Industrial Technology (ICIT 2016), TF-006254, Tapei, Taiwan, March 14-17.

[9] Diaf, S., Daif, D., Haddadi, M., and Louche, A. 2007. "A Methodology for Optimal Sizing of Autonomous Hybrid PV/Wind System." *Energy Policy* 35 (11): 5708-18.

[10] Borowy, B. S., and Salameh, Z. M. 1996. "Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System." *IEEE Transactions on Energy Conversion* 11 (2): 367-75.

[11] Hongxing, Y., Lin, L., and Wei, Z. 2007. "A Novel Optimization Sizing Model for Hybrid Solar-Wind Power Generation System." *Solar Energy* 81 (1): 76-84.

[12] Mohammad, M. S., Masahiro, F., Mohammed, E. L., Atsushi, Y., and Tomonobu, S. 2017. "Optimal Economical Sizing of Grid-Connected Hybrid Renewable Energy System." *Journal of Energy and Power Engineering* 11: 244-53.

[13] Satish, K. R., and Bibhuti, B. R. 2014. "Optimal Design of a Hybrid PV-Wind Energy System Using Genetic Algorithm (GA)." *International Journal of Engineering Research & Technology (IJERT)* 3 (1): 1902-11.

[14] Harun Or Rashid, H., Abdul Matin, I., Toshihisa, F., and Tomonobu, S. 2017. "Optimal ESSs and Demand Response Can Help to Make Profitable Optimal Thermal UC in Case of High Penetration of PVs." TENCON 2017-2017 IEEE Region 10 Conference, Penang, Malaysia, November 5-8.

[15] Punyisa, K., and Udom, J. 2018. "A Comparative Study of Mixed-Integer Linear Programming and Genetic Algorithms for Solving Binary Problems." In 5th International Conference on Industrial Engineering and Applications, Singapore, Singapore, April 26-28.