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# EFFECT OF BATTERY ENERGY STORAGE SYSTEMS ON THE VALUE OF AN INTERMITTENT WIND ENERGY SOURCE IN ISOLATED SYSTEMS


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# EFFECT OF BATTERY ENERGY STORAGE SYSTEMS ON THE VALUE OF AN INTERMITTENT WIND ENERGY SOURCE IN ISOLATED SYSTEMS

Chun-Lung Chen

Key words: unit commitment, wind energy system, battery energy storage system, improved dynamic programming, hybrid direct search method.

## ABSTRACT

The increase in environmental protection awareness and the progressive exhaustion of conventional fossil energy sources have increased interests in integrating wind energy sources into existing power systems. Despite the various benefits of wind power, the intermittency and unpredictability of wind power generation cause operational concerns and waste usable capacity as the installation of the wind generation sources increases. To enhance the value of an intermittent wind energy source by using a battery energy storage system (BESS), an iterative algorithm that combines improved dynamic programming and a hybrid direct search method were developed for solving the optimal wind-thermal-battery coordination scheduling (WTBCS) problem in power systems. Key concerns in BESSs and the integration of wind energy and electric power systems were investigated and discussed using the proposed WTBCS software. In addition, the developed WTBCS software is useful in assessing the effect and economic benefits of installing BESSs and wind farms. Numerical experiments were conducted to provide information for both operational and planning problems in isolated power systems, such as the Penghu power system.

## I. INTRODUCTION

With intensifying global energy concerns, wind energy technologies offer attractive economic solutions for wind-abundant remote areas frequently facing power supply problems. Because of the recent rapid reduction in the cost of wind turbine generators (WTGs), installing WTGs for fuel saving is economically and environmentally feasible in windy regions. To demonstrate the effectiveness of wind power generation, the Taiwan Power Company (Taipower) installed eight wind generators with a capacity of 600 kW each on the Penghu offshore island. Increasing the power supply capacity in the Penghu power system by installing utility (or nonutility) power plants utilizing wind energy sources is beneficial (Wu et al., 2011). Despite the various benefits of wind power, the intermittency and unpredictability of wind power generation complicates frequency control and generation scheduling and may cause operational concerns and waste usable capacity as WTG installation increases. Therefore, understanding the wind energy utilization factor (WUF; the ratio of actual to available wind generation) and capacity of wind generation systems is critical in analyzing production costs, and provides a favorable indicator to site new wind power plants in isolated power systems, such as in Penghu. Many problems can arise in renewable energy-based hybrid power systems, particularly in system operating and planning (Demeo Edgar et al., 2005; Georgilakis, 2006; Albadi and El-Saadany, 2009).

Large-scale integration of wind power plants affects several power system-related concerns, including optimal power flow, economic dispatch, unit commitment (UC), transmission congestion, power quality, system stability, and system economics (Jabr and Pal, 2009; Morales et al., 2009; Billinton and Aboreshaid, 2010; Wang et al., 2011; Wu et al., 2013). A crucial future challenge is managing the integration of fluctuations in electricity production from wind energy sources (Chen et al., 2006). Another principal concern regarding the integration of wind energy generation in a public utility is the evaluation of system spinning reserve (Doherty and O'Malley, 2005; Chen, 2007). Several energy storage devices, such as battery energy storage systems (BESSs), pumped storage, and superconducting magnetic energy storage systems, have been investigated to improve the system economic efficiency and utilization (Lee, 2007; Brown et al., 2008; Lee, 2008; Nomura et al., 2010; Daneshi and Srivastava, 2012). Furthermore, studies have discussed the value of bulk energy storage in

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managing wind power fluctuations and the effect of energy storage on spinning reserve requirements (Habibi, 2001; Black and Strbac, 2007). However, few studies have considered the effects of BESSs on the value of an intermittent wind energy source in isolated systems. As wind power penetration increases in isolated power systems, an enhanced understanding of improving WUF by using BESSs is essential for optimally exploiting wind energy sources. The importance of wind-thermal-battery coordination scheduling (WTBCS) is thus likely to increase in managing the high fluctuations in wind power generation and improving the WUF of wind generation systems in the Penghu power system.

The UC problem is an extremely complex nonlinear mixed-integer programming problem, which is further complicated by WTGs and BESSs. Owing to its complexity and high computational requirements, research efforts have been concentrated on efficient, heuristic UC algorithms, which can be applied to realistic power systems. Literature on the application of optimization methods to generation scheduling is vast. Previous UC methods (Bakirtzis and Petridis, 1966; Bakirtzis and Dokopulos, 1988; Wood and Wollenberg, 1996; Juste et al., 1999; Zhao et al., 2006; Chen et al., 2008; Logenthiran and Srinivasan, 2009), including priority list, dynamic programming (DP), Lagrangian relaxation approach, simulated annealing (SA), genetic algorithm, evolutionary programming, and particle swarm optimization, can solve the extended UC problem. To effectively overcome the coupling constraints of the WTBCS problem, an iterative algorithm that combines improved DP (IDP) and a hybrid direct search method (HDSM) was developed in this study to solve the optimal generation schedule problem for hybrid power systems. The developed WTBCS computation tool is useful in addressing the following key BESS (or wind) integration issues:

Issue 1: How can the WTBCS problem in the Penghu power system be solved?

Issue 2: What is the dispatch policy of the operating reserves for managing the high fluctuations and limited predictability of wind power generation in the isolated Penghu power system?

Issue 3: What are the effects of the technique constraints on the WUF of wind energy sources?

Issue 4: What are the effects of the BESS capacity on WUF and operating cost?

Issue 5: Which methodology provides useful information for installing BESSs and WTGs for fuel saving in the Penghu power system?

This study determined the operating schedule of a BESS for a wind-thermal hybrid power system that minimizes the total operating cost and satisfies the operational constraints. The developed software maximizes the contribution of wind farms and BESSs in reducing the cost of thermal dispatch. In addition, the developed software is useful in assessing the effect and economic benefits of installing BESSs and wind farms. Test results illustrate the merits of the proposed method and provide an understanding of BESSs and wind generator capacity in the operating cost analysis of the Penghu power system.

## II. MATHEMATICAL FORMULATION OF THE WTBCS PROBLEM

### 1. Notation

The following notation is used throughout the paper.

| | |
|---|---|
| $a_i$, $b_i$, $c_i$ | : cost coefficients of thermal unit i |
| $CS_{1,t}$ | : penalty term for Eq. (3) |
| $CS_{2,t}$ | : penalty term for Eq. (4) |
| $CS_{3,t}$ | : penalty term for Eqs. (17)-(18) |
| $CS_{4,t}$ | : penalty term for Eq. (19) |
| $CS_{5,t}$ | : penalty term for Eq. (20) |
| $d\%$ | : percentage of maximum unit capacity |
| $DR_{bat}(t)$ | : ramping down rate of battery at hour t |
| $DR_i(t)$ | : ramping down rate of thermal unit i at hour t |
| $DR_i^{\max}$ | : maximum ramp-down rate for thermal unit i |
| $DS_{bat}(t)$ | : down reserve contribution of battery at hour t |
| $DS_i(t)$ | : down reserve contribution of thermal unit i at hour t |
| $DS_i^{\max}$ | : maximum down reserve contribution of thermal unit i |
| $F_i(\bullet)$ | : operation cost function of thermal unit i |
| $F_T$ | : total operating cost |
| $i$ | : index for thermal units |
| $j$ | : index for wind units |
| $NT$ | : number of thermal units in the system |
| $NW$ | : number of wind units in the system |
| $P_{bat}(t)$ | : power output of battery at hour t (positive for discharging and negative for charging) |
| $P_{bat}^{\max}$ | : maximum power output of battery |
| $P_i(\mathrm{t})$ | : generation of thermal unit i at hour t |
| $P_{i,r}^{\max}$ | : upper generation limit of thermal unit i |
| $P_{i,r}^{\min}$ | : lower generation limit of thermal unit i |
| $P_i^{\max}(t)$ | : maximum generation of thermal unit i at hour t because of ramp-up rate constraint |
| $P_i^{\min}(t)$ | : minimum generation of thermal unit i at hour t because of ramp-down rate constraint |
| $P_D(t)$ | : system load demand at hour t |
| $P_{Wj}^{\max}$ | : upper generation limit of wind unit j |
| $P_{Wj}^{*}(t)$ | : available generation of wind unit j at hour t |
| $P_{Wj}(t)$ | : actual generation of wind unit j at hour t |
| $P_{WT}^{*}(t)$ | : total available wind generation at hour t |
| $P_{WT}(t)$ | : total actual wind generation at hour t |
| $r\%$ | : percentage of actual wind power generation |

| | |
|---|---|
| $r_b$ | : penalty factor |
| $SOC(t)$ | : energy left in the battery at hour t |
| $SOC_{\min}$ | : minimum energy left in the battery |
| $SOC_{\max}$ | : maximum energy left in the battery |
| $SR_i$ | : startup ramp rate limit of thermal unit i |
| $t$ | : index for time intervals (hours) |
| $T$ | : number of time intervals (hours) |
| $T_{on,i}$ | : minimum up time of thermal unit i |
| $T_{off,i}$ | : minimum down time of thermal unit i |
| $t_{on,i}(t)$ | : time period that thermal unit i had been continuously up till period t |
| $t_{off,i}(t)$ | : time period that thermal unit i had been continuously down till period t |
| $u_i(t)$ | : scheduled state of thermal unit i for hour t (1: unit i is up, 0: unit i is down) |
| $USR_B$ | : basic up-spinning reserve requirement (not considering wind power generation) |
| $UR_{bat}(t)$ | : ramping up rate of battery at hour t |
| $UR_i(t)$ | : ramping up rate of thermal unit i at hour t |
| $UR_i^{\max}$ | : maximum ramp-up rate for thermal unit i |
| $US_{bat}(t)$ | : up reserve contribution of battery at hour t |
| $US_i(t)$ | : up reserve contribution of thermal unit i at hour t |
| $US_i^{\max}$ | : maximum up reserve contribution of thermal unit i |
| $v(t)$ | : wind speed at hour t |
| $v_{Ij}$ | : cut in wind speed of wind unit j |
| $v_{Rj}$ | : rated wind speed of wind unit j |
| $v_{Oj}$ | : cut out wind speed of wind unit j |
| $\varphi_j(\bullet)$ | : wind power curve of wind unit j |
| $\xi\%$ | : percentage of system load demand |
| $\eta_B$ | : battery efficiency during the charging/discharging period |
| $\Delta t$ | : time interval |

## 2. Formulation

The main objective of solving the WTBCS problem is to determine when to start-up and shut- down units, so that the total operating cost can be minimized, while simultaneously satisfying the "system" and the "generator" constraints. Because of the intermittency and unpredictability of wind power generation, additional physical and economic operation constraints must be taken into consideration to reach a compromise between system security and total operating cost. It can be formulated as follows:

Objective function:

$$Minimize\ \ F_T = \sum_{t=1}^{T}\sum_{i=1}^{NT} F_i(P_i(t)) \tag{1}$$

The system and generator constraints for the WTBCS problem are shown as follows:

*1) System Constraints*

- Power balance constraint

$$\sum_{i=1}^{NT} u_i(t)\times P_i(t) + P_{WT}(t) + P_{bat}(t) = P_D(t) \tag{2}$$

- System up/down spinning reserve requirements

$$\sum_{i=1}^{NT} u_i(t)\times US_i(t) + US_{bat}(t) \ge USR_B + r\%\times P_{WT}(t) \tag{3}$$

$$\sum_{i=1}^{NT} u_i(t)\times DS_i(t) + DS_{bat}(t) \ge r\%\times P_{WT}(t) \tag{4}$$

*2) Thermal Unit Constraints*

- Unit generation limits

$$P_i^{\min}(t)\times u_i(t) \le P_i(t) \le P_i^{\max}(t)\times u_i(t) \tag{5}$$

where

$$P_i^{\max}(t) = \begin{cases} \min\{P_{i,r}^{\max},\ P_i(t-1)+UR_i^{\max}\}, & if \quad u_i(t)=u_i(t-1)=1, \\ \min\{P_{i,r}^{\max},\ P_i(t-1)+SR_i\}, & if \quad u_i(t)=1, u_i(t-1)=0. \end{cases} \tag{6}$$

$$P_i^{\min}(t) = \begin{cases} \max\{P_{i,r}^{\min},\ P_i(t-1)-DR_i^{\max}\}, & if \quad u_i(t)=u_i(t-1)=1, \\ P_{i,r}^{\min} & if \quad u_i(t)=1, u_i(t-1)=0. \end{cases} \tag{7}$$

- Unit's maximum up/down reserve contribution constraints

$$US_i^{\max} = d\%\times P_{i,r}^{\max} \tag{8}$$

$$DS_i^{\max} = d\%\times P_{i,r}^{\max} \tag{9}$$

- Unit's up/down spinning reserve contribution constraints

$$US_i(t) = \min\left\{US_i^{\max},\ P_i^{\max}(t) - P_i(t)\right\} \tag{10}$$

$$DS_i(t) = \min\left\{DS_i^{\max},\ P_i(t) - P_i^{\min}(t)\right\} \tag{11}$$

- Minimum up/down time constraints

$$[t_{on,i}(t-1) - T_{on,i}]\times[u_i(t-1) - u_i(t)] \ge 0 \tag{12}$$

$$[t_{off,i}(t-1) - T_{off,i}]\times[u_i(t) - u_i(t-1)] \ge 0 \tag{13}$$

*3) Wind Unit Constraints*

- Wind power curve constraints

$$P_{Wj}^{*}(t) = \begin{cases} 0 & v(t)\le v_{Ij}\ or\ v(t) > v_{Oj} \\ \varphi_j(v(t)) & v_{Ij}\le v(t)\le v_{Rj} \\ P_{Wj}^{\max} & v_{Rj}\le v(t)\le v_{Oj} \end{cases} \tag{14}$$

- Total available wind generation

$$P_{WT}^{*}(t)=\sum_{j=1}^{NW}P_{Wj}^{*}(t) \quad (15)$$

- Total actual wind power generation limit

$$0\leq P_{WT}(t)\leq P_{WT}^{*}(t) \quad (16)$$

- Wind generation fluctuation constraints

$$P_{WT}(t)-P_{WT}(t-1)\leq\sum_{i=1}^{NT}u_i(t)\times DR_i(t)+DR_{bat}(t) \quad if\ P_{WT}(t-1)\leq P_{WT}(t) \quad (17)$$

$$P_{WT}(t-1)-P_{WT}(t)\leq\sum_{i=1}^{NT}u_i(t)\times UR_i(t)+UR_{bat}(t) \quad if\ P_{WT}(t-1)\geq P_{WT}(t) \quad (18)$$

- Wind power penetration limit

$$P_{WT}(t)\leq\xi\%\times P_D(t) \quad (19)$$

*4) Battery Constraints*

- Charge/discharge power limits

$$-P_{bat}^{\max}\leq P_{bat}(t)\leq P_{bat}^{\max} \quad (20)$$

- State of charge limits

$$SOC_{\min}\leq SOC(t)\leq SOC_{\max} \quad (21)$$

$$SOC(0)=SOC_S \quad \text{initial state of charge} \quad (22)$$

$$SOC(T)=SOC_E \quad \text{final state of charge} \quad (23)$$

- State of charge balance equation

$$SOC(t)=SOC(t-1)-P_{bat}(t)\times\eta_B\times\Delta t \quad if \quad P_{bat}(t)<0 \quad (24)$$

$$SOC(t)=SOC(t-1)-P_{bat}(t)\times\frac{\Delta t}{\eta_B} \quad if \quad P_{bat}(t)\geq 0 \quad (25)$$

- Battery's up/down spinning reserve contribution constraints

$$US_{bat}(t)=\min\left\{P_{bat}^{\max}-P_{bat}(t),P_{bat}^{\max},\frac{SOC(t)-SOC_{\min}}{\Delta t}\times\eta_B\right\} \quad (26)$$

$$DS_{bat}(t)=\min\left\{P_{bat}^{\max}+P_{bat}(t),P_{bat}^{\max},\frac{SOC_{\max}-SOC(t)}{\eta_B\times\Delta t}\right\} \quad (27)$$

## III. DEVELOPMENT OF THE WTBCS COMPUTATION TOOL

Including the wind unit, thermal unit, and BESS constraints requires the coordination of power generation over the entire dispatch period, resulting in extreme augmentation of the execution time. To effectively overcome with the coupling constraints of the WTBCS problem, the proposed iterative algorithm decomposes the coordination problem into wind-thermal and battery subproblems. The IDP was used for solving the wind-thermal subproblem and the HDSM was used for solving the wind-thermal-battery dispatch subproblem according to the thermal UC results. These schemes iterate between the two subproblems until the solutions converge. The computational steps of the proposed algorithm are as follows:

Step 1: Read system data and parameters and set initial conditions.
Step 2: Estimate the initial solution of the energy stored in a BESS.
Step 3: Set iter = 1.
Step 4: Optimize the wind-thermal generating UC by using IDP when the BESS dispatch solution freezes.
Step 5: Optimize the wind-thermal-battery dispatch by using the HDSM when the thermal UC solution (on/off status of thermal units) freezes.
Step 6: If the schedules have converged, print the results; otherwise, set iter = iter + 1 and go to step 4.

The proposed WTBCS problem-based iterative algorithm is detailed in the following sections.

### 1. Initial Estimate of the Energy Stored in the BESS

Electrical energy stored in the BESS was used as the state variable in this study. To reduce the number of iterations for solving the WTBCS problem, an extension of the DSM, described in Section 3.3, was developed for solving the initial energy trajectory of the BESS. The operating constraints of the wind and thermal units were released at this stage. The computational steps of this stage are as follows:

Step 1: Read the system data.
Step 2: Calculate the total available wind power generation for each hour ($P_{WT}^{*}(t)$) using the wind power curve.
Step 3: Shave the load demand by using the WTG power output.

$$P_D^{new}(t)=P_D(t)-P_{WT}^{*}(t) \quad t=1,2,\ldots,T \quad (28)$$

Step 4: Solve the initial BESS energy trajectory by using the HDSM to achieve the objection function as (29)

$$Minimize\ EP_D(t)=\sum_{t=1}^{T}(P_D^{new}(t))^2 \quad (29)$$

Step 5: The initial output of the BESS is as indicated in (30)

$$\left[P_{bat}^{0}(1) \quad P_{bat}^{0}(2) \quad \ldots \quad P_{bat}^{0}(T)\right] \tag{30}$$

## 2. Optimal Wind-Thermal Generating UC Using IDP

The DP approach is of particular interest because it can solve multiple problems and easily handle operating constraints. In a DP algorithm, the time horizon is divided into smaller (usually hourly) time stages. In every stage (or hour), the corresponding states representing different combinations of commitment status (on/off) for the generating units in that specific period were specified. A path then represented a transition from one state of a given stage to another state of the next stage. Such transitions may necessitate the starting or shutting of certain units. Thus, the UC problem can be recursively solved using forward dynamic programming, which systematically evaluates the accumulated cost associated with each commitment path and backtracks the least cost path at the last stage to find the optimal solution. However, many problems exist in this solution process (see Section 3.2.1). In this study, DP was extended for optimally scheduling wind and thermal generating units during the dispatch period, and the reserve constrained economic dispatch subproblem was solved through a conventional DSM routine (Chen et al., 2006). The operating schedule of the BESS was frozen at this stage. The proposed IDP is detailed herein:

*1) Drawbacks of the DP Method*

The main drawback of the DP method is its dimensionality. For practicality of the enumeration process considering the limited computing resources, the solution space is typically truncated and only certain potential states for next-stage computations are reserved. The selection of saved states at each time stage is vital to the success of truncated DP (TDP) (Wood and Wollenberg, 1996). In general, as the number of saved paths increases, more potential states of units yielding economic schedules are retained for decreasing the system operating cost. However, for a high number of saved low cost paths, the cost saturates, because TDP saves many identical states (or similar states) and thus some economic states are excluded at some stages. The conventional TDP is reviewed in Fig. 1 to illustrate the choice of the saved states. For simplicity, five states (A-E) were considered and three lowest cost paths were saved at each time stage. The solid lines represent the three lowest cost paths (path 1, 2, and 3) between states and the dashed lines represent high cost paths, which have been dropped. No line is observed between states if the transition is infeasible. Suppose three states A, B, and D are saved at stage $t$ because they point to the same state B; then, only state B is saved at stage $t+1$. This results in a nonoptimal solution. The conventional TDP requires further research and development for obtaining accurate dispatch results.

*2) Enhancing the DP*

The number of potential states saved at each time stage is termed as "population". To maintain population diversity, a novel replacement strategy for preventing premature convergence is to monitor the states allowed into the population. The enhanced TDP is illustrated in Fig. 2. Three states in each stage were saved, and only the lowest-cost path (e.g., $L$ = 1) was saved in each different state. Although this process may not be economic currently, it has the potential to decrease operating costs in the future. The worst case is termed full DP (FDP), where all possible states are considered in each stage. To reduce the adverse effect of time-dependent constraints, several low-cost paths (e.g., $L$ = 2) can also be saved in each different state. The further process of enhanced TDP (e.g., $Cn$ = 3 and $L$ = 2) is presented in Fig. 3. When the number of different states equals the specified value, the search process terminates. The proposed IDP algorithm for solving the wind-thermal coordination schedule involves the following steps (Chen, 2014):

Step 1: Read the system data.
Step 2: Set time counter $t$ = 1.
Step 3: Calculate the total available wind power generation ( $P_{WT}^{*}(t)$ ) at hour $t$.

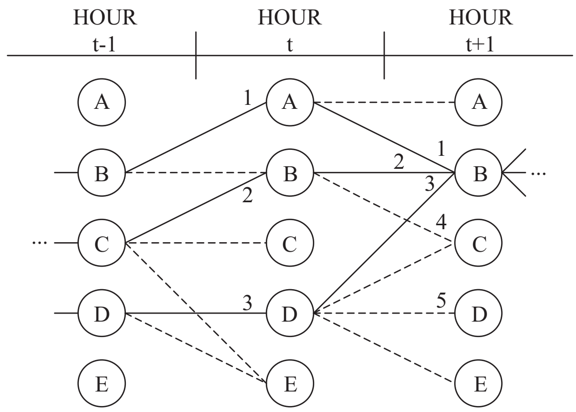


**Fig. 1. Process of conventional TDP algorithm with *Cn* = 3.**

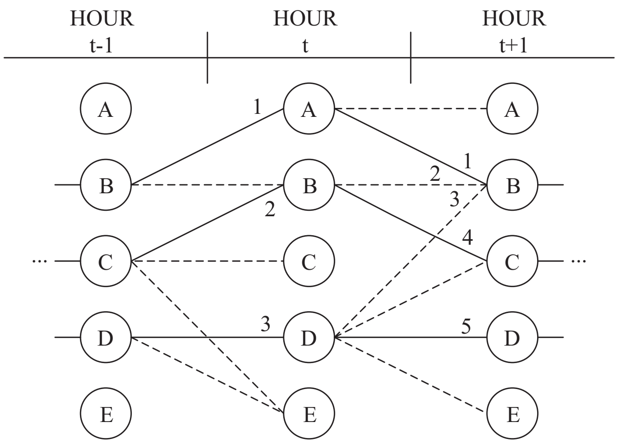


**Fig. 2. Process of enhanced TDP algorithm with *Cn* = 3 and *L* = 1.**

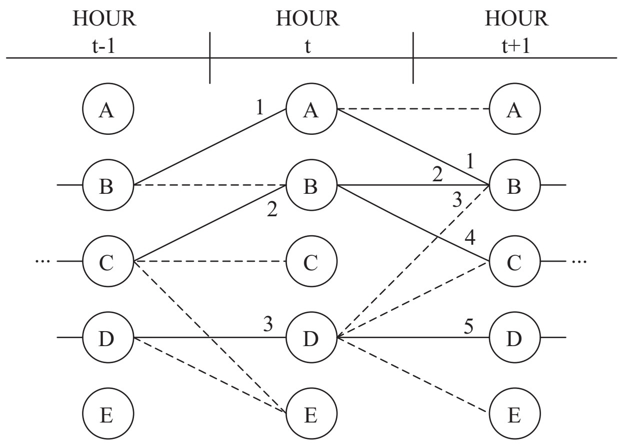


**Fig. 3. Process of enhanced TDP algorithm with $Cn$ = 3 and $L$ = 2.**

Step 4: Shave the load demand by using the BESS power output at hour $t$.

$$P_D^{new}(t) = P_D(t) - P_{bat}(t) \tag{31}$$

Step 5: Determine the appropriate search range at hour $t$ by using the previously saved lowest-cost state.
Step 6: Apply several technique constraints to determine the actual wind power generation ($P_{WT}(t)$) for a state.
Step 7: Calculate the system up/down spinning reserve requirements for a state.
Step 8: Load to be supplied by the thermal units is dispatched using the conventional DSM algorithm to calculate the production cost and power generation of each unit.
Step 9: Go to step 6 for the next state; otherwise, go to step 10.
Step 10: If any previously saved states must be searched, go to step 5; otherwise, go to step 11.
Step 11: Save Cn potential states for next-stage computations.
Step 12: If $t < T$, all saved states are sorted by their cost; set $t = t + 1$and go to step 3.
Step 13: Trace the optimal schedule.

## 3. Optimal Wind-Thermal-Battery Scheduling Using HDSM

Incorporating an additional BESS into the existing wind-thermal generation scheduling problem further complicates the solution methodology because of the coupling constraints of the system spinning requirements, actual wind power generation, and power balance. This study is an extension of previous studies on DSM solution and optimizes the wind-thermal-battery dispatch according to the thermal UC results. The proposed HDSM algorithm basically incorporates DP in the DSM to augment the searching technique. An effective strategy based on a successive refinement search technique was then used to guarantee a possibly complete examination of the solution space. To accelerate the process, multilevel convergence was used for improving the convergence property during successive iterations. The proposed HDSM approach involves the following steps:

Step 1: Read the system data.
Step 2: Use the results of battery generation schedule from the previous iteration as the starting point.
Step 3: Set the proper values of initial step size $S_1$ and reduced factor $K$.
Step 4: $S = S_1$
Step 5: Perform direct search by using three-state DP.
Step 6: If $S$ is greater than the predefined resolution $\varepsilon$, $S = S/K$, go to step 5; otherwise, stop.

The proposed HDSM is detailed in the following section.

### *1) Solution Improvement Using HDSM*

Exploration on initialization begins with finding the most suitable direction for improvement. To find a direction that reduces the operating cost and leads to a point within the feasible region, the procedure may be required to augment the searching technique for an extended generation scheduling problem. The DP is an effective direct search procedure for achieving the maximal reduction in the total operating cost. The system constraints were treated differently. Most operating constraints were appropriately handled during the direct search procedure. To account for up-reserve requirement (3), down-reserve requirement (4), wind generation fluctuation (17), (18), wind power penetration limit (19), and battery charge/discharge power limit violations (20), the total operating cost was augmented by nonnegative penalty terms $CS_{1,t}$, $CS_{2,t}$, $CS_{3,t}$, $CS_{4,t}$, and $CS_{5,t}$, respectively, penalizing constraint violations. Thus, the augmented cost function is formed as

$$F_{TA} = F_T + \sum_{b=1}^{5}(r_b \sum_{t=1}^{T} CS_{b,t}) \tag{32}$$

The penalty terms ($CS_{1,t}$ – $CS_{5,t}$)) are proportional to the corresponding violations and equals zero in case of no violations. The penalty terms are chosen adequately high to render constraint violations prohibitive in the final solution. The computational steps of the direct search procedure are as follows:

Step 1: Set iter = 1
Step 2: Without violating the $SOC_{\max}$ or $SOC_{\min}$, increase or decrease the battery output using the predefined step $S$ to determine the state transition diagram for DP. Only three possible states ($SOC(t) + S$, $SOC(t)$, and $SOC(t)$-$S$) are tested at each hour.
Step 3: The most suitable charging/discharging trajectory of the battery was determined using the three-state DP to minimize the total operating cost $F_{TA}$.
Step 4: Calculate if there is improvement in the total operating cost. If no more improvement can be achieved, stop; otherwise, go to step 5.

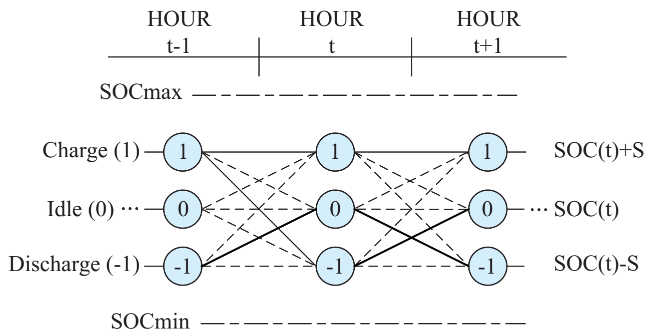


**Fig. 4. State transition diagram of BESS for DP.**

Step 5: Project the charging/discharging trajectory of battery, $SOC(t)$, $t = 1, 2, \ldots, T$.
Step 6: iter = iter + 1, and go to step 2.

During successive iterations, the solution was improved repeatedly and all violations of the system constraints were appropriately eliminated. After first level convergence, the step size was successively refined using $S = S/K$ (where reduced factor $K > 1$) during each convergence level until the calculation was less than the predetermined resolution $\varepsilon$ (e.g., $\varepsilon = 0.01$ MW).

*2) Optimal Charging/Discharging Trajectory of the Battery Using DP*

The DP algorithm optimized the charging/discharging trajectory of the battery. Fig. 4 depicts the state transition diagram of the BESS for DP. We defined the charged, idle, and discharged state of battery as 1, 0, -1, respectively. Three possible states ($SOC(t) + S$, $SOC(t)$, and $SOC(t)$-$S$) were examined every hour. After a potential state was revealed, the total output power generation of the thermal units was calculated using Eq. (2), and the conventional DSM used the economic dispatch module for obtaining the accumulated production costs of each saved state for the next hour. Thus, the generation scheduling problem was recursively solved using forward DP, which systematically evaluated the accumulated operating cost associated with each commitment path, and backtracked the least operating cost path at the last stage to determine the optimal solution. The proposed DP algorithm is as follows:

Step 1: Read the system data and set the initial conditions.
Step 2: Set time counter $t = 1$.
Step 3: Find the search range at hour $t$.
Step 4: Determine the actual wind power generation at hour $t$ by using several technique constraints.
Step 5: Calculate the system up/down spinning reserve requirements at hour $t$.
Step 6: Calculate the load to be supplied by the thermal units by using Eq. (2) to determine the operating cost of a state.
Step 7: Go to step 6 for the next state; otherwise, go to step 8.
Step 8: Save the lowest operating cost strategy for each state.
Step 9: If $t < T$, set $t = t + 1$and go to step 3.
Step 10: Trace the optimal schedule.

## IV. NUMERICAL EXAMPLES

To verify the feasibility and effectiveness of the proposed algorithm, several test systems were studied. All computations were performed on a Pentium (R) Dual CPU 2.00 GHz computer with 1.0 GB RAM. The studied cases are detailed herein.

### 1. Example 1: Testing a 10-Unit Thermal System with An Equivalent Wind Generator

In the first example, a 10-unit thermal system with an equivalent wind generator was studied to illustrate the merits of the proposed algorithm. The system unit data and load demand have been determined in (Chen, 2007). The generator and startup ramp rate constraints were set at 60% of the rated capacity. The increased up/down spinning reserve requirement was calculated as a simple fraction of the total actual wind power generation (r% = 20%) to compensate for possible fluctuations in WTG power. The maximum up/down spinning reserve of any single thermal unit cannot contribute more than 10% of its rated capacity (d% = 10%). For simplicity, the available wind power generation of the equivalent wind generator was assumed to be 400 MW for all periods. In addition, the system up spinning reserve requirement without considering wind generation was assumed to be 200 MW. Table 1 reports the numerical experimental results for illustrating the effects of wind capacity integration on operating cost. The results obtained using the proposed IDP were compared with those obtained using previously published methods, such as SA (Chen, 2007) and FDP. The total average cost of the SA and IDP algorithms are \$69,791.29 and \$69,700.95, respectively, in Case 1.2. In Case 1.3, the proposed IDP with $Cn$ = 20 and $L$ = 2 (\$66,253.90) outperforms the FDP method (\$66,263.87). The drawback of the FDP method lies in tackling time-dependent constraints, leading to suboptimal solutions. Consequently, the optimal power output of the equivalent wind generator was determined by the proposed algorithm to minimize the total operating cost of the system.

### 2. Example 2: Testing a Wind-Thermal System with a BESS

In this example, a simulated BESS with a capacity of 300 MWh/30 MW was integrated in the wind-thermal system considered in Example 1. The minimum SOC was limited to 20% and the charging/discharging efficiency was 0.9. The initial/end state of charge is set to 250 MW. The effects of WTGs and BESSs on the total operating cost of the proposed system are reported in Table 2. In the previous system, if WTGs and BESSs were excluded, the total operating cost was \$79,203.24 in Case 2.1. As shown in Case 2.2, 16.3% of the operating cost was saved when the system included the WTGs.

**Table 1. Comparison of results in example system 1.**

| Case | Available wind power generation (MW) | SA | FDP | IDP | |
|---|---|---|---|---|---|
| | | | | $Cn = 20$ $L = 1$ | $Cn = 20$ $L = 2$ |
| | | Average cost ($) | Operating cost ($) | Operating cost ($) | Operating cost ($) |
| 1.1 | $P^*_{WT}(t) = 0$ | 79235.41 | 79203.24 | 79203.24 | 79203.24 |
| 1.2 | $P^*_{WT}(t) = 200$ | 69791.29 | 69700.95 | 69700.95 | 69700.95 |
| 1.3 | $P^*_{WT}(t) = 400$ | 66283.80 | 66263.87 | 66263.87 | 66253.90 |

**Table 2. Comparison of operating cost saving under various simulation cases in example system 2.**

| Test case | WTGs | BESS | WUF(%) | Operating cost($) | Saving (%) |
|---|---|---|---|---|---|
| 2.1 | Without | Without | --- | 79203.24 | --- |
| 2.2 | With | Without | 72.6% | 66253.90 | 16.3% |
| 2.3 | With | With | 91.5% | 61665.46 | 22.1% |

**Table 3. Determined commitment schedule not considering BESS using the proposed algorithm for example system 2.**

| Unit | Commitment state from hour 1-24 |
|---|---|
| 1 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 1 1 1 1 1 1 1 |
| 2 | 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 1 1 1 1 1 1 1 1 |
| 3 | 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 1 1 1 1 1 1 1 |
| 4 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 5 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 6 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 7 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 8 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 9 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 10 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| Total operating cost ($) : 66253.90 | |

**Table 4. Determined commitment schedule considering BESS using the proposed algorithm for example system 2.**

| Unit | Commitment state from hour 1-24 |
|---|---|
| 1 | 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 |
| 2 | 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 1 1 1 1 1 1 1 |
| 3 | 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 |
| 4 | 0 1 1 1 1 1 1 1 11 1 0 0 1 1 1 1 1 1 1 1 1 1 1 |
| 5 | 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 |
| 6 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 7 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 8 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 9 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| 10 | 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 |
| Total operating cost ($) : 61665.46 | |

Installing one 300 MWh/30 MW BESS saved an additional 22.1% of the operating cost (Case 2.3). The results from the simulation exercise are useful in aiding decisions regarding capital investment in WTGs (or BESSs) for the isolated power system.

To illustrate the effect of incorporating a BESS into the wind-thermal system on the existing utility generation scheduling problem, Tables 3 and 4 compare the determined commitment schedules in the absence and presence of a BESS in the proposed algorithm. The intermittency of wind generation requires the running of a more flexible plant than necessary otherwise to satisfy system reserve requirements in the absence of a BESS. As shown in Fig. 5, further curtailing the wind generator outputs during low system loads is cost effective (hour 11-17). However, as a BESS was integrated into this system, the WUF increased from 72.6% to 92.5%. Fig. 6 shows the electrical energy changes in the BESS. The BESS was fully charged during the light load hours when fuel was cheap, and then discharged during peak load hours. This function saves energy costs and reduces risks of the BESS running out of energy during peak demand reduction. To demonstrate the acceptable convergence of the proposed HDSM algorithm, Table 5 compares the total iterations required for and the operating costs during each convergence level. The proposed HDSM algorithm determines an optimal operating cost ($61,875.49) at the first iteration between wind-thermal and battery subproblems. Only five iterations were required between the two subproblems to reach the final solution (Table 6). The process is iterative and therefore the solution may be a local optimum instead of a global one. However, all cases tested in this research converge to reasonable solutions agree with engineering intuition. In this test case, the proposed iterative algorithm obtained the satisfactory solution ($61,665.46) in approximately 24 s.

### 3. Example 3: Penghu Power System Test

In the final example, the proposed approach was numerically tested on the Penghu wind-diesel power system for 8760 h

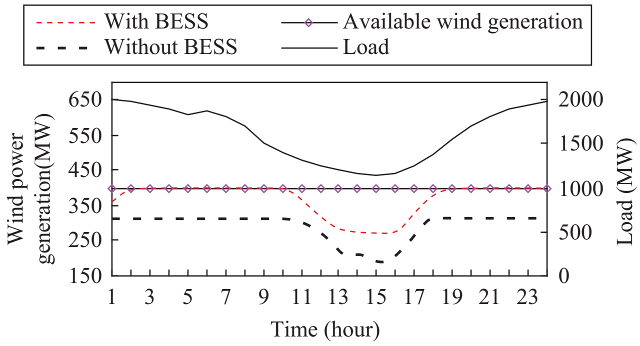


**Fig. 5. Scheduling of actual wind power generation considering BESS or not for example system 2.**

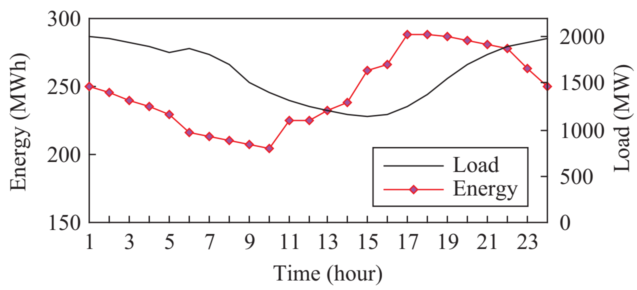


**Fig. 6. Electrical energy changes in the BESS for example system 2.**

(Chen et al., 2008). The wind-diesel system consists of 12 diesel units of total capacity 120,000 kW and a wind farm with eight identical 600-kW wind generators (Enercon E40-600 kW turbine). In this study, all the wind generators were assumed to have the same cut-in, rated, and cut-out wind speeds (2.5, 13, and 25 m/s, respectively). Diesel units can operate between 40%-100% of their rated capacity. The minimum up/down time constraints of the diesel units were considered in the IDP process for avoiding frequent stopping and starting. The yearly mean wind speed over the Penghu offshore island is approximately 9.88 m/s at a height of 45 m. The computer program HOMER (National Renewable Energy Laboratories, 2003) was applied to generate annual hourly wind speed data for chronological simulation. The maximum and minimum loads for the study period of 8760 h were 20,748 and 64,268 kW, respectively. HOMER was also applied to modify the original load data with daily noise = 10% and hourly noise = 10% to consider the effects of load uncertainty and load growth. Only the system up reserve requirement (10,000 kW) was required to cover the potential loss of the largest unit in the system. To compensate for possible fluctuations in WTG power, the increased up/down spinning reserve requirements were calculated as a simple fraction of the predicted wind generation (r% = 20%). The maximum up/down spinning reserve of any single thermal unit cannot contribute more than 20% of its rated capacity (d% = 20%). The maximum wind power penetration was restricted to 40% of the system load demand ($\xi$% = 40%). The generator and startup ramp rate

**Table 5. Performance of proposed HDSM algorithm at the first iteration between wind-thermal and battery sub-problems in example system 2.**

| Convergence | Iterations | Operating cost ($) |
|---|---|---|
| Initialization | --- | 63929.13 |
| S1 = 30 MW | 4 | 62100.88 |
| S2 = 6 MW | 15 | 61920.77 |
| S3 = 1.2 MW | 14 | 61880.73 |
| S4 = 0.24 MW | 22 | 61876.48 |
| S5 = 0.048 MW | 14 | 61875.49 |

**Table 6. Performance of proposed iterative algorithm in example system 2.**

| Iteration | Operating cost ($) |
|---|---|
| 1 | 61875.49 |
| 2 | 61770.19 |
| 3 | 61675.45 |
| 4 | 61665.46 |
| 5 | 61665.46 |

constraints were set at 60% of their rated capacities. The developed software is useful for a system planner to predict the energy cost and fuel saving from the new wind-diesel-battery systems. The following key concerns of BESS (or wind) capacity integration in the Penghu power system were investigated using the developed UC computation tool.

To assess the effect and economic benefits of installing WTGs, wind farms were operated with installed capacities ranging from 0 kW (0 × 600 kW) to 28,800 kW (48 × 600 kW). The developed UC software was used to simulate system operation by considering and disregarding wind power generation for one year. The new wind capacity integration necessitated an update of the energy flow control strategies of each component to fully explore the wind-diesel energy system benefits. Wind capacity integration requires scheduling an additional emergency reserve, which significantly increases operating costs; nevertheless, Table 7 reveals that the total operating costs decrease as the number of installed WTGs increase. The fuel cost saving generated by the WTGs is higher than the costs added by the additional up/down reserve requirements. However, because of the system operating constraints, the production cost savings did not change significantly (24.56%) when the number of installed WTGs was 48. Moreover, the utilization factor of wind energy sources decreased to 46.07%. These numerical results are indicators that provide information for installing WTGs as fuel savers in the Penghu power system.

To illustrate the improvement in WUF and production cost savings when incorporating BESS in the Penghu power system, a simulated battery with a capacity of 1050 kWh/350 kW was considered. Table 8 lists the substantial benefits of annual operational cost savings as the number of the installed 600 kW

**Table 7. Comparison of fuel saving under various NW without BESS for the Penghu power system.**

| Case | WTGs | BESS | WUF(%) | TC($10^6$NT$) | Saving (%) |
|---|---|---|---|---|---|
| 3.1.1 | 0kW | Without | --- | 98.523 | --- |
| 3.1.2 | 8 * 600 kW | Without | 94.09% | 89.799 | 8.85% |
| 3.1.3 | 16 * 600 kW | Without | 79.59% | 84.259 | 14.48% |
| 3.1.4 | 28 * 600 kW | Without | 63.01% | 79.063 | 19.75% |
| 3.1.5 | 36 * 600 kW | Without | 55.10% | 76.713 | 22.13% |
| 3.1.6 | 48 * 600 kW | Without | 46.07% | 74.326 | 24.56% |

**Table 8. Comparison of fuel saving under various NW considering BESS or not for the Penghu power system.**

| Case | WTGs | BESS | WUF(%) | TC($10^6$NT$) | Saving (%) |
|---|---|---|---|---|---|
| 3.2.1 | 8 * 600 kW | Without | 94.09% | 89.799 | --- |
| | | With | 95.65% | 89.572 | 0.252% |
| 3.2.2 | 16 * 600kW | Without | 79.59% | 84.259 | --- |
| | | With | 82.87% | 83.651 | 0.721% |
| 3.2.3 | 28 * 600kW | Without | 63.01% | 79.063 | --- |
| | | With | 65.17% | 78.340 | 0.914% |
| 3.2.4 | 36 * 600kW | Without | 55.10% | 76.713 | --- |
| | | With | 56.91% | 75.929 | 1.022% |
| 3.2.5 | 48 * 600kW | Without | 46.07% | 74.326 | --- |
| | | With | 47.56% | 73.437 | 1.195% |

**Table 9. Comparison of fuel saving under various BESS capacity for the Penghu power system.**

| Case | BESS | WUF(%) | TC($10^6$NT$) | Saving (%) |
|---|---|---|---|---|
| 3.3.1 | Without | 46.07% | 74.326 | --- |
| 3.3.2 | 1050 kWh/350 kW | 47.56% | 73.437 | 1.195% |
| 3.3.3 | 3150 kWh/1050 kW | 50.42% | 72.154 | 2.922% |
| 3.3.4 | 6300 kWh/2100 kW | 53.25% | 70.871 | 4.648% |

WTGs increases. The annual cost savings did not change significantly (0.252%) when 8 WTGs were installed. However, a significant annual cost saving of 1.195% was realized when 48 WTGs were installed. The results showed that the value of an intermittent wind energy source can be increased by using BESS. Table 9 presents an analysis of the WUF and annual operational cost saved under various BESS capacities when 48 WTGs were installed. A significant increase (53.25%-47.56% = 5.68%) in WUF was observed when the BESS capacity was increased from 1050/350 kW to 6300 kWh/2100 kW, and annual operational cost savings increased from 1.195% to 4.648%. The results showed that BESS is one of the most promising technologies for improving the system economic efficiency and utilization as wind power penetration increases in isolated power systems.

## V. CONCLUSIONS

This study developed an iterative algorithm that combines IDP and the HDSM for solving the WTBCS problem. Several new major concepts about the UC module were investigated for large-scale wind capacity integration. The results showed that the algorithm is a reliable approach and that the solution is reasonable. In addition, the results demonstrated that BESS is one of the most promising technologies for increasing the value of an intermittent wind energy source and reducing the operating cost of a power system. The computer program developed is currently being experimentally added to an energy management system as auxiliary software to support service to power companies. In real-time application, the proposed WTBCS software can determine the optimal operating policy for the next time stage. This function can maximize the contribution of wind farms and BESS for reducing the cost of thermal dispatch. In offline applications, the proposed WTBCS software is useful in aiding decisions regarding capital investment in wind energy sources. Numerical experiments were included to provide a favorable indication of whether to invest in new power plants by integrating wind energy sources or invest in BESS for the Penghu power system.

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