Security-constrained unit commitment with wind generation and compressed air energy storage

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Abstract: Wind power is one of the fastest growing renewable sources of generation in the U.S. and many other countries. As wind-generated electricity continues to grow, electric utilities increasingly grapple with the challenges of connecting that power to the grid although maintaining system security. It is difficult to predict and control the output of wind generation because of wind intermittency and a reserve capacity is required to deal with inherent uncertainty. This study presents an approach for security-constrained unit commitment (SCUC) with integration of an energy storage system (ESS) and wind generation. Compressed air energy storage (CAES) is considered as an alternative solution to store energy. For economical operation and control purposes, utilities with CAES are interested in the availability and the dispatch of CAES on an hourly basis, given the specific characteristics of CAES. The main contribution of this study is the development of enhanced SCUC formulation and solution techniques with wind power, CAES and multiple constraints including fuel and emission limit. Proposed approach allows simultaneous optimisation of the energy and the ancillary services (AS). Case studies with eight-bus and 118-bus systems are presented to validate the proposed model. This study also contributes by conducting comprehensive studies to analyse the impact of CAES system on locational pricing, economics, peak-load shaving, transmission congestion management, wind curtailment and environmental perspective.

Nomenclature

- $\alpha_k^w$: efficiency factor of CAES in generation mode
- $\alpha_k^{inj}$: efficiency factor of CAES in compression mode
- $A_{k,t}$: inventory level at time $t$
- $A_{k,max}$: maximum capacity of CAES in MWh
- $A_{k,min}$: minimum capacity of CAES in MWh
- $b$: bus index
- $E_{max}$: system emission limit
- $F_i(\cdot)$: production cost function of unit $i$
- $F_i^f(\cdot)$: fuel consumption function of unit $i$
- $F_i^e(\cdot)$: emission function of unit $i$
- $F_{min}^{FT}$: minimum fuel consumption of fuel type $FT$
- $F_{max}^{FT}$: maximum fuel consumption of fuel type $FT$
- $FL_{l,t}$: flow of line $l$ at time $t$
- $FL_{l,max}$: maximum flow of line $l$
- $FT$: index for fuel type
- $i$: denote a thermal unit
- $I$: set of thermal units
- $k$: denote a CAES unit
- $K$: set of CAESs
- $l$: line index
- $L$: number of lines
- $MU_i$, $MD_i$: minimum up/down time of a unit
- $nr_{i,t}$: non-spinning reserve of unit $i$ at time $t$
- $P_{D,t}$: forecasted load at time $t$
- $P_{i,t}$: active power generation of unit $i$ at time $t$
- $P_{i,min}$, $P_{i,max}$: minimum/maximum active power generation
- $P_{k,min}$, $P_{k,max}$: minimum/maximum pumping capacity of CAES
- $P_L$: system losses at time $t$
- $Q_{SC_i}$: quick start capability of unit $i$
- $Q_{i,t}$: reactive power generation of unit $i$ at time $t$
- $Q_{i,min}$, $Q_{i,max}$: minimum/maximum reactive power generation
- $rd_{i,t}$: regulation down of unit $i$ at time $t$
- $R_{N,t}$: system non-spinning reserve requirement at $t$
1 Introduction

Global concerns over climate change and sustainability have led to a recent worldwide push towards electricity derived from renewable and sustainable resources. Among renewable resources, wind generation has grown substantially, and additional growth is projected in future years. The increase in world installed wind capacity has been impressive with an average annual growth of more than 30% over the last 5 years [1–4]. Assessing the impact of wind power on unit commitment (UC) and dispatch is a fundamental issue when integrating more intermittent wind power into power systems. In many areas in U.S., for example in Texas, highest wind generation may occur during off-peak hours when the demand is low [5].

One possibility to achieve higher system flexibility is energy-storage investment. In this paper, compressed air energy storage (CAES) is considered to store electricity. CAES is designed to draw excess power from other resources off the grid and drive an electric air compressor. The compressed air is stored in an underground storage cavern. The efficiency of a generator with CAES plant is approximately three times the efficiency of a simple gas turbine configuration.

This paper presents a formulation for solving the security-constrained unit commitment (SCUC) problem with wind power and CAES; and studying its impact on several power system operational parameters. The objective of SCUC in a restructured power system is to obtain a commitment schedule for generation units at minimum production cost with several unit/system constraints. Unit constraints include minimum on/off time, ramping up/down, minimum/maximum generation limit, fuel and emission limit. The system constraints include transmission security constraints such as voltage limits on buses, power flow limits on selected lines and selected interfaces [6–12]. The SCUC problem is decomposed into two coordinated problems, based on Benders decomposition technique, which include a master problem for optimising UC and a sub-problem for minimising network violations. Modelling for wind uncertainty/intermittency has not been considered, but can be easily included based on other uncertainty modelling efforts reported in the literature (as indicated in Section 3.2). Contributions of this paper are to develop a comprehensive formulation of SCUC with CAES and wind generation as well as to conduct case studies to show the impact of CAES on both economical and technical aspects. Proposed approach allows simultaneous optimisation of energy and ancillary services (AS) with storage.

2 Background

2.1 Wind energy outlook

In 2008, the U.S. Department of Energy (DOE) published a report that examined the technical feasibility of using wind energy to generate 20% of the nation’s electricity demand by 2030 [1, 2]. In its energy outlook 2007, the U.S. Energy Information Administration (EIA) estimates that U.S. electricity demand will grow by 39% from 2005 to 2030 reaching 5.8 billion megawatt-hours (MWh) by 2030. To meet 20% of that demand, U.S. wind power capacity would have to reach more than 300 GW. This growth represents an increase of more than 290 GW within 23 years.

As installed wind capacity grows more than 10% of the demand in a given region, the intermittency of wind energy may become an operational issue. Fortunately, a number of new technologies and deployment strategies are making wind energy friendly, and promising continued growth in its share of total energy. These include better wind forecast, advanced power-electronic devices, enhanced-control techniques and energy storage.

2.2 Energy storage

Although power system may operate effectively without storage, cost-effective ways of storing electrical energy can help make the grid more efficient and reliable. Also combining wind generation with energy storage system (ESS) provides a proper solution for mitigating volatility and intermittency of wind energy. It is difficult to store electricity directly; but electric energy can be stored in other forms, such as potential, chemical, magnetic or kinetic energy. Energy storage can bring several other benefits providing...
additional flexibility to the system including load management, transmission enhancement, AS and positive environmental impact. Today, different types of ESS technologies with different characteristics are being developed of which some are available commercially although others are still in the development stage. There are several criteria for comparing and selecting ESS technology. Comparison of ESSs and their characteristics including their advantages and disadvantages are provided in [13, 14].

CAES has been in use as a peak shaving option since 1970s. The first CAES plant, a 290 MW facility, was started in Huntorf, Germany in 1978 [15]. A 110 MW plant commenced operation in McIntosh, Alabama in 1991 [16]. The Iowa Association of Municipal Utilities is developing a 268 MW CAES project in Dallas Center, Iowa [17].

Literature on CAES and wind power generation is just starting to grow. In [18], a stochastic model is used to estimate the effects of significant wind power generation on system operation and economic value of investments in CAES. Salgi and Lund [19] analyses the energy balance effects of adding CAES to the Western Danish power system. Salgi and Lund [20] assess the value of integrating CAES into future sustainable energy systems with higher renewable energy fluctuation. The Danish case is evaluated in a system-economic perspective by comparing the economic benefits achieved by improving the integration of wind power to CAES. The result is compared with various other storage options. Different solutions to energy storage including CAES have been discussed in [21]. Enis et al. [22] describe the advantage of using CAES coupled with wind. Another study provides an economic evaluation concerning the installation of a CAES system for a private wind energy surplus on the island of Crete [23]. A basic formulation of SCUC problem emphasising on wind power and CAES is presented in [24]. Garcia-Gonzalez et al. [25] investigate the impact of pumped-storage on system with high wind penetration. There are also several papers that address main technical challenges associated with the integration of wind power into power systems [26–29]. These challenges include effects of wind power on the power system, operating cost, power quality, power imbalances, power system dynamics and impacts on transmission planning. Basic formulation and study presented in [24] have been extended in this paper to provide a comprehensive formulation of SCUC with CAES including the way a CAES can participate in AS market. Several different scenarios for two-test case systems are further provided in case studies to show the impact of CAES on locational marginal price (LMP), mitigating transmission congestions, environmental limit, peak-shaving, system operational cost, wind curtailment and price of AS. Future work will involve including the intermittency of wind based on the literature [30, 31] in the developed SCUC formulation.

3 SCUC formulation with CAES

The objective function is formulated as follows

$$\text{Min} \sum_{i=1}^{T} \left \{ \sum_{j=1}^{I} \left [ \sum_{l=1}^{K} \left ( F_{i}^{l} (P_{i,l}) u_{i,l} + ST_{i,l} + SD_{i,l} \right ) + \sum_{k=1}^{K} F_{i}^{k} (P_{i,k}) u_{i,k} \right ] \right \}$$

(1)

where the first term represents thermal operating cost including fuel, startup and shutdown costs; the second term represents the operating cost of CAES units over the scheduling horizon. The operating costs of wind units are assumed to be zero. The list of symbols is presented in the Nomenclature section.

The constraints listed next include the system energy balance (2), required spinning reserve (3), non-spinning reserve (4), regulation up (5), regulation down (6), ramping limits (7a), (7b), minimum On/Off time limits (8a), (8b), active and reactive power generation limits (9), (10), transmission line flow limit (11) and bus voltage limit (12). System constraints such as fuel constraints (13) and emission limits (14) are included in this formulation.

$$\sum_{i=1}^{I} P_{i,l} + \sum_{k=1}^{K} P_{i,k} + W_{i} = P_{D,l} + P_{L,l}, \; \forall t$$

(2)

$$\sum_{i=1}^{I} s_{i} + \sum_{k=1}^{K} s_{k} \geq R_{S}, \; \forall t$$

(3)

$$\sum_{i=1}^{I} n_{i} + \sum_{k=1}^{K} n_{k} \geq R_{N}, \; \forall t$$

(4)

$$\sum_{i=1}^{I} r_{i} + \sum_{k=1}^{K} r_{k} \geq R_{R}, \; \forall t$$

(5)

$$\sum_{i=1}^{I} r_{d,i} + \sum_{k=1}^{K} r_{d,k} \geq R_{RD}, \; \forall t$$

(6)

$$P_{i,t+1} - P_{i,t} \leq RU_{i} (1 - y_{i,t}) + P_{i,min} y_{i,t}, \; \forall i, \forall t$$

(7a)

$$P_{i,t} - P_{i,t+1} \leq RD_{i} (1 - z_{i,t}) + P_{i,min} z_{i,t}, \; \forall i, \forall t$$

(7b)

$$\sum_{j=1}^{J} (1 - u_{j,t}) = 0, \; \forall i$$

$$\text{max} \{T_{i} + \mu U_{i}/l - 1\}$$

(8a)

$$UT_{i} = \text{MAX} \{0, \text{MIN}[T_{i} (MU_{i} - TU_{i} (0, H_{U0}))], \; \forall i$$

(8b)

$$P_{i,min} u_{i,t} \leq P_{i,t} \leq P_{i,max} u_{i,t}, \; \forall i, \forall t$$

(9)

$$Q_{i,min} u_{i,t} \leq Q_{i,t} \leq Q_{i,max} u_{i,t}, \; \forall i, \forall t$$

(10)

$$-FL_{b}^{i} \leq FL_{b}^{i} \leq FL_{b}^{i} \; \forall b, \forall t$$

(11)

$$v_{min} \leq v_{b} \leq v_{max} \; \forall b, \forall t$$

(12)

$$F_{FT}^{\text{min}} = \sum_{i=1}^{I} \sum_{l=1}^{L} \left [ F_{i}^{l} (P_{i,l}) u_{i,l} + ST_{i,l} + SD_{i,l} \right ]$$

$$+ \sum_{k=1}^{K} F_{i}^{k} (P_{i,k}) u_{i,k} \leq F_{FT}^{\text{max}}$$

(13)

$$\sum_{i=1}^{I} \sum_{l=1}^{L} \left [ F_{i}^{l} (P_{i,l}) u_{i,l} + ST_{i,l} + SD_{i,l} \right ] + \sum_{k=1}^{K} F_{i}^{k} (P_{i,k}) u_{i,k} \leq E_{max}$$

(14)

Developed formulations of objective function and constraints for SCUC are inspired by [6–12]. We assume generation cost, fuel consumption and emission are expressed as a function of power dispatch. The electricity generated from
wind turbine in (2) is known through short-term forecasting. \( P_{k,t} \) in (2) represents hourly generation and compression of CAES in MW where negative value corresponds to the compressor mode.

Basic formulation for SCUC including CAES model and coordination with wind was presented in [24] and further extended in this paper by adding additional system constraints for regulation up/down, fuel and emission for representing the interactions among electricity market, fuel market and environment. Additionally, CAES modelling has been extending in this paper by adding constraints to model CAES participation in AS market using (21)–(27).

In our proposed optimisation model, the following modes for CAES are considered:

- **Idling**: when CAES is not operating as either generator or compressor.
- **Compressor**: when system load is low, then electricity is used to compress air into an underground storage cavern.
- **Generator**: when electricity is needed, the compressed air is returned to the surface, heated by natural gas and run through turbine to produce electricity.

To include all mentioned modes in our model, the following integer variables and constraints are introduced

\[ u_{k,t} = 1 \text{ in generation mode and } 0 \text{ either in idle or compressor mode.} \]
\[ u_{c,t} = 1 \text{ in compressor mode and } 0 \text{ in idle or generation mode.} \]

\[ u_{k,t} + u_{c,t} \leq 1 \quad \forall k, \forall t \quad (15) \]

Minimisation of the total production cost to meet the demand including compression loads will automatically impact injection and withdrawal. The cost related to compression is reflected in generation cost and the efficiency through co-optimisation. Cost of producing \( P_k \) MW of electricity by CAES is equal to gas price multiplied by heat-rate value for generating \( P_k \), which is represented by a piecewise linear function in (1). The other constraints are presented as follows

\[ P_{k,t} = a_k^w v_{k,t} - a_k^i v_{c,t}, \quad \forall k, \forall t \quad (16) \]
\[ v_{k,max} u_{k,t} - v_{k,min} u_{k,t} \leq v_{k,t} \leq v_{k,max} u_{k,t}, \quad \forall k, \forall t \quad (17) \]
\[ v_{c,min} u_{c,t} - v_{c,max} u_{c,t} \leq v_{c,t} \leq v_{c,max} u_{c,t}, \quad \forall k, \forall t \quad (18) \]

where (16) represents the linear relation between volume of air released from storage and amount of power produced by CAES. In compressor mode, the amount of compressed air is limited to the maximum capacity of the cavern minus the current inventory level.

\[ A_{k,t+1} = A_{k,t} + v_{c,t} - v_{k,t}, \quad \forall k, \forall t \quad (19) \]
\[ A_{k,min} \leq A_{k,t} \leq A_{k,max}, \quad \forall k, \forall t \quad (20) \]

The rapid response of a CAES enables it to provide both energy service and AS. The awarded quantity for non-spinning reserve (NSR) is equal to gas price multiplied by heating rate value for generation \( P_k \), which is represented as

\[ P_{k,min} u_{k,t} - P_{k,max} u_{k,t} \leq P_{k,t} \leq P_{k,max} u_{k,t} - P_{k,min} u_{k,t}, \quad \forall k, \forall t \quad (21) \]

Although the CAES is in compressor mode, the loaded capacity of the compressor could be considered as spinning reserve or regulation up, since in an emergency the compressor could be treated as interruptible load. In generation mode, the unloaded capacity could be considered to be spinning reserve or regulation up.

\[ r_{u,k,t} \leq u_{k,t} R_{k,t} T_{ru} + u_{c,t} R_{c,t} T_{ru}, \quad \forall k, \forall t \quad (22) \]
\[ s_{r,k,t} \leq u_{k,t} R_{k,t} T_{sr} + u_{c,t} R_{c,t} T_{sr}, \quad \forall k, \forall t \quad (23) \]

It can also provide regulation down in either generator or compressor mode.

\[ r_{d,k,t} \leq u_{k,t} R_{k,t} T_{rd} + u_{c,t} R_{c,t} T_{rd}, \quad \forall k, \forall t \quad (24) \]

The awarded quantity for non-spinning reserve in generator, compressor and idle mode is expressed as follows

\[ n_{r,k,t} \leq u_{k,t} R_{k,t} T_{nr} + u_{c,t} R_{c,t} T_{nr} + (1 - u_{k,t} - u_{c,t}) QSC_k, \quad \forall k, \forall t \quad (25) \]

A CAES, once generating, must maintain minimum output. In addition, if it provides regulation down, it must operate more than minimum capacity to be able to provide regulation down capacity. It can also participate in regulation of down market in compressor mode by withdrawing more energy from network. In this case, it must operate less than maximum compression size to make room for regulation down. Such constraints are described as follows

\[ P_{k,t} + r_{d,k,t} \geq P_{k,min} u_{k,t} - P_{k,max} u_{c,t}, \quad \forall k, \forall t \quad (26) \]

The total amount of energy, regulation up, spinning reserve and non-spinning reserve should not exceed the maximum generation capacity of CAES in generator mode.

\[ P_{k,t} + r_{u,k,t} + s_{r,k,t} + n_{r,k,t} \leq u_{k,t} P_{k,max} - u_{c,t} P_{c,min} + (1 - u_{k,t} - u_{c,t}) QSC_k, \quad \forall k, \forall t \quad (27) \]

Mathematically SCUC is a problem with an objective to be minimised with respect to a series of equality and inequality constraints. The problem is large-scaled, mixed-integer and non-linear. Benders decomposition technique is applied to decompose such an optimisation problem into a master problem for solving UC, feasibility check sub-problems and network security check sub-problems as shown in Fig. 1.

The detailed discussion on Benders decomposition is presented in [32].

The master UC, which includes objective function (1) and constraints (2)–(27), provides the schedule and dispatch solution for minimising the operation cost without transmission security constraint. Various techniques, such as dynamic programming, Lagrangian relaxation, mixed-integer programming (MIP), genetic algorithm and expert systems have been applied to solve UC problem. In this study, CPLEX was employed to solve master problem.
Once the master problem is solved, the network security check is solved for every hour, as shown in Fig. 1. This sub-problem will check whether the current commitment and dispatch solution of the master problem violates security constraints. If any violations persist, the sub-problem will form the corresponding Benders cut for the master problem in the next iteration of UC. The mitigation of violations will result in the final SCUC solution.

4 Case studies

Two case studies consisting of an eight-bus and IEEE 118-bus system are used to illustrate the performance of the proposed model that considers the integration of wind and CAES. The impact of CAES is analysed based on economic indices such as operation costs, LMP, wind curtailment, load shaving, environmental impact and transmission congestion.

4.1 Eight-bus system

To focus on key issues, a simple eight-bus system is used in Fig. 2. There are six thermal units (G1–G6), one wind unit (W), a CAES (S) and ten transmission lines. The wind unit and storage are located at Bus 2. The characteristics of CAES, thermal units, buses and transmission lines are listed in Tables 1–3, respectively. The CAES has maximum generation and compressing capacity of 100 MW, minimum generation and compressing capacity of 5 MW. The storage is assumed to be large enough to store enough energy to generate at maximum capacity for 5 h, that is, 500 MWh. The study period is 24-h. The 24-h system load and forecasted wind power are presented in Table 4. As shown in Fig. 2, system is divided into two zones. All wind generations are in Zone 1, and far from load centre. About 80% of total load is located in Zone 2. It is assumed that there is not enough transmission capacity to transfer all wind generation at peak hours.

The following scenarios are discussed in this paper:

Case 1: Base case without CAES unit. The example includes six thermal units and a wind.

Table 1 Parameters of CAES

<table>
<thead>
<tr>
<th>Unit</th>
<th>Bus</th>
<th>( \alpha_{\min} )</th>
<th>( \alpha_{\max} )</th>
<th>( \nu_{\min}^w )</th>
<th>( \nu_{\min}^f )</th>
<th>( \nu_{\max}^f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAES</td>
<td>2</td>
<td>50</td>
<td>500</td>
<td>5</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 2 Parameters of thermal units

<table>
<thead>
<tr>
<th>Unit</th>
<th>Bus</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( P_{\min} )</th>
<th>( P_{\max} )</th>
<th>( L_{\min} )</th>
<th>( L_{\max} )</th>
<th>( ST )</th>
<th>( \alpha_{\min} )</th>
<th>( \alpha_{\max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>6</td>
<td>0.01</td>
<td>22.94</td>
<td>58.81</td>
<td>25</td>
<td>70</td>
<td>300</td>
<td>500</td>
<td>300</td>
<td>0.01</td>
<td>0.025</td>
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<tr>
<td>G2</td>
<td>7</td>
<td>0.002</td>
<td>12.33</td>
<td>28</td>
<td>50</td>
<td>250</td>
<td>300</td>
<td>500</td>
<td>300</td>
<td>0.005</td>
<td>0.02</td>
</tr>
<tr>
<td>G3</td>
<td>8</td>
<td>0.013</td>
<td>17.82</td>
<td>10.15</td>
<td>25</td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>0.013</td>
<td>0.029</td>
</tr>
<tr>
<td>G4</td>
<td>4</td>
<td>0.27</td>
<td>20</td>
<td>300</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>0.27</td>
<td>0.33</td>
</tr>
<tr>
<td>G5</td>
<td>4</td>
<td>0.27</td>
<td>18.5</td>
<td>300</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>0.27</td>
<td>0.33</td>
</tr>
<tr>
<td>G6</td>
<td>4</td>
<td>0.27</td>
<td>22</td>
<td>350</td>
<td>30</td>
<td>150</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.27</td>
<td>0.33</td>
</tr>
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</table>

Table 3 Transmission line parameters

<table>
<thead>
<tr>
<th>Line no.</th>
<th>From bus</th>
<th>To bus</th>
<th>( X ) (pu)</th>
<th>Line limit (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0.099</td>
<td>150</td>
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<td>2</td>
<td>2</td>
<td>3</td>
<td>0.042</td>
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<td>4</td>
<td>3</td>
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<td>0.108</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>6</td>
<td>0.021</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>7</td>
<td>0.031</td>
<td>300</td>
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<td>9</td>
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<tr>
<td>10</td>
<td>3</td>
<td>4</td>
<td>0.108</td>
<td>60</td>
</tr>
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</table>

Table 4 Forecasted load demand and wind power

<table>
<thead>
<tr>
<th>Hour</th>
<th>Wind (MW)</th>
<th>Load (MW)</th>
<th>Hour</th>
<th>Wind (MW)</th>
<th>Load (MW)</th>
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<tbody>
<tr>
<td>1</td>
<td>162.17</td>
<td>509.10</td>
<td>12</td>
<td>142.30</td>
<td>541.31</td>
</tr>
<tr>
<td>2</td>
<td>162.99</td>
<td>469.74</td>
<td>13</td>
<td>148.29</td>
<td>571.14</td>
</tr>
<tr>
<td>3</td>
<td>151.82</td>
<td>441.92</td>
<td>14</td>
<td>96.90</td>
<td>602.61</td>
</tr>
<tr>
<td>4</td>
<td>168.00</td>
<td>423.57</td>
<td>15</td>
<td>72.27</td>
<td>627.76</td>
</tr>
<tr>
<td>5</td>
<td>161.94</td>
<td>409.33</td>
<td>16</td>
<td>42.20</td>
<td>647.09</td>
</tr>
<tr>
<td>6</td>
<td>144.18</td>
<td>402.32</td>
<td>17</td>
<td>42.20</td>
<td>663.34</td>
</tr>
<tr>
<td>7</td>
<td>168.00</td>
<td>409.15</td>
<td>18</td>
<td>63.39</td>
<td>655.66</td>
</tr>
<tr>
<td>8</td>
<td>148.53</td>
<td>410.64</td>
<td>19</td>
<td>74.21</td>
<td>636.80</td>
</tr>
<tr>
<td>9</td>
<td>113.60</td>
<td>441.44</td>
<td>20</td>
<td>79.62</td>
<td>643.62</td>
</tr>
<tr>
<td>10</td>
<td>114.90</td>
<td>480.02</td>
<td>21</td>
<td>102.90</td>
<td>628.27</td>
</tr>
<tr>
<td>11</td>
<td>125.01</td>
<td>512.38</td>
<td>22</td>
<td>131.22</td>
<td>583.54</td>
</tr>
</tbody>
</table>

Fig. 1 Security-constrained unit commitment

Fig. 2 One-line diagram of eight-bus system
Case 2: A CAES is installed at Bus 2 close to the wind resource. In this case, we observe the impact of CAES on system operation and compare generation dispatch and total system operating cost with and without CAES.

Case 3: We also analyse the impact of CAES by relocating it from Bus 2 to Bus 8, close to load centre.

Case 4: Comparison between bulk storage and distributed storage. We install two CAESs, one at wind bus and another close to load centre.

Based on above four cases the following criteria are discussed:

- Impact of CAES on LMP.
- Impact of CAES on mitigating transmission congestions.
- CAES and environmental impact.
- CAES and peak-shaving.
- Impact of CAES on system operation cost.
- Wind curtailment.
- Price of AS.

All cases in this section are calculated using a Pentium IV, 3 GHz personal computer with 1 GB RAM. Fuel and emission constraints are not enforced in this specific example to analyse the impact on environment.

4.1.1 Case 1: SCUC result without CAES: In this case, we assume there is no CAES. The 24-h system load and wind profile are listed in Table 4 in which the peak load is 667.26 MW at hour 19. We solve the SCUC and determine the commitment and dispatch of units. The commitment schedule is shown in Table 5 in which 1/0 represent hourly ON/OFF status of units. In addition, the hourly generation dispatch is given in Table 6. It is assumed that the fuel price is $/MBtu and spinning reserve, regulation up and down are 5, 2 and 2% of the load, respectively.

The cheaper units G2 and G3 are always committed and dispatched to supply the base load. The more expensive unit G1 is committed between hours 15 and 23, when wind is low and load is high. Comparing wind generation in Table 6 with forecasted hourly wind profile in Table 5 indicates that wind is curtailed at peak-wind hours because of limited transmission capacity from Zone 1 to Zone 2. Daily generation dispatch cost is $211 646.1.

4.1.2 Case 2: SCUC result with CAES at Bus 2: To observe the impact of CAES, we add a CAES unit at Bus 2 with available wind resource. The efficiency factors ($\alpha_k^{\text{c}}$, $\alpha_k^{\text{g}}$) for compression and generation are 95%. The load and wind profile are same as Case 1. Table 7 presents the UC with CAES for 24 h.

In this case, the expensive unit G1 is committed from hour 13 to 18, which is less than Case 1. When wind is high, demand is low at Zone 1, and there is not enough transmission capacity to transfer wind energy to Zone 2. CAES is used to store extra wind energy. Lower generation dispatch cost of $204 177.5 is obtained in Case 2 when CAES unit is added compared with higher cost in Case 1 before adding CAES. In our analysis, we are not considering the comparative capital investment for the installation of CAES assuming that payback period is already over.

4.1.3 Case 3: SCUC result with CAES at Bus 8: We also analyse the impact of CAES at locations other than wind bus, such as near the load centre. Therefore we relocate it from Bus 2 to Bus 8. In this case, CAES can provide on-peak energy where load is relatively high, and also provide reliable capacity close to load. The commitment schedules are given in Table 8. Hourly wind generation shows curtailment of wind at peak hours because of transmission limit from Zone 1 to Zone 2.

Generation dispatch cost of $202 445.5 is obtained which is slightly lower than Case 2. It can be seen that adding storage close to the load centre can provide a reliable resource for the customer. Adding storage close to load will decrease system losses. System loss is higher at peak hours.
since loss is proportional to line resistance and square of the current magnitude. Therefore CAES store electricity at off-peak hours when system loss is low and serve the load locally at peak hours instead of using transmission lines.

4.1.4 Case 4: SCUC result with distributed CAES: In this section, we install two CAESs half the size of the one in Cases 2 and 3. We locate a CAES at Bus 2 where the wind is injected and another one at Bus 8 close to the load centre. In this case, one CAES can store wind at off-peak hours when demand is low or the transmission line is congested to prevent wind curtailment. The second storage provides reliable resource close to the load, which prevents unserved energy. This configuration enjoys the advantage of both Cases 2 and 3. The commitment schedules are given in Table 9. The total dispatch cost of $196 859.0 is lower than in the last three cases. Wind curtailment is non-zero.

4.1.5 Impact of CAES on LMP: Currently, most wind resources are located in remote areas where transmission interconnections are usually limited. During peak hours, line flows could reach their upper limits and create congestion in the system. Once congestions occur, the power from cheaper units may not be fully utilised which will increase the LMP at various buses.

As indicated earlier, CAES could be installed to remedy transmission congestion problems. The lack of congestion in such system will reduce LMPs and dispatch cost. Fig. 3 shows hourly LMP at Bus 5. Results indicate that CAES degrades the peak and off-peak price differential by raising off-peak prices and depressing peak prices. In Case 4, price is elevated at off peak hours because of air compression, and it is dropped down at peak hours because of CAES generation. In Case 2, the CAES is in Zone 1 and cannot supply the load in Zone 2 because of limited transmission capability. The additional dispatch will be necessary in this case since the cheaper generation resources cannot be fully utilised, because of the branch 4 congestion, to satisfy the load at Bus 5. The congestion on branch 4 will result in large LMPs at Bus 5 as represented by curve in Fig. 3. The congestion on branch 4 is eliminated by utilising the CAES at Bus 8 or distributed in the system as mentioned earlier in Cases 3 and 4. The reduction in LMP will impact the cost of supplying the load at the corresponding bus.

Fig. 4 shows hourly LMP at Bus 2 in which the wind generation is injected. It can be seen that adding CAES at wind bus make the LMP smoother by raising the off-peak price and dropping the peak price.

4.1.6 Wind curtailment: Wind curtailment is projected because of the availability of adequate transmission to support the available wind production. In this example, during off-peak hours, when the wind is high, it cannot be fully dispatched because of congestion on branch 4.

Fig. 5 shows hourly wind curtailment in percentage. In Case 2, CAES is located at Bus 2 close to wind resource and has lowest wind curtailment. Comparing hourly wind generation and forecasted value shows that the curtailment is zero in Case 2. In Case 4, there are still some wind curtailments despite the CAES at same bus that the wind is located. The curtailment is because of the storage size. Case

Table 8 SCUC result with CAES at Bus 8 (Case 3)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Hours (0–24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>000000 00000 00000 111111 1110</td>
</tr>
<tr>
<td>G2</td>
<td>111111 111111 111111 111111</td>
</tr>
<tr>
<td>G3</td>
<td>111111 111111 111111 111111</td>
</tr>
<tr>
<td>G4</td>
<td>000000 000000 001111 111111</td>
</tr>
<tr>
<td>G5</td>
<td>111000 000000 011111 111111</td>
</tr>
<tr>
<td>G6</td>
<td>000000 000000 000001 111111</td>
</tr>
</tbody>
</table>

Table 9 SCUC result with distributed CAES (Case 4)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Hours (0–24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>000000 00000 00000 111111 11111</td>
</tr>
<tr>
<td>G2</td>
<td>111111 111111 111111 111111</td>
</tr>
<tr>
<td>G3</td>
<td>111111 111111 111111 111111</td>
</tr>
<tr>
<td>G4</td>
<td>000000 000000 001111 111111</td>
</tr>
<tr>
<td>G5</td>
<td>111000 000000 011111 111111</td>
</tr>
<tr>
<td>G6</td>
<td>000000 000000 000001 111111</td>
</tr>
</tbody>
</table>
with higher percentage of coal generation, the coal units may be most economical at off-peak hours. In this case, it is required to burn more coal at off-peak hours when the CAES is in compressor mode, which will increase total emission.

4.1.10 Impact of CAES on system operation cost:
The operation costs are shown in Fig. 7, which range from $196 859.00 for Case 4 to $211 646.03 for Case 1. In this test case example, we analysed the results without CAES and with CAES on different locations. Simulation results show the investments in CAES increase the efficiency of the electricity system, lower the costs and emission and make the system more reliable. It is observed that adding CAES close to both the load centre and wind location will have the best results in terms of cost, emission, congestion and wind curtailment for this particular case study. Capital cost and feasibility may be considered to obtain more practical test case results with same developed formulation.

4.1.11 Impact of CAES on AS price:
With increasing installed wind capacity, there is recognition that this intermittent generation resource may increase grid volatility, requiring more AS to help maintain reliability grid operations. As we discussed in Section 4, CAES can provide different AS in both compression and generation mode. In this section we analyse the impact of CAES on AS price. It is assumed that the system requirement for spinning reserve, regulation up and down is 5, 2 and 2% of the load, respectively. Fig. 8 shows the hourly price for regulation up for all four cases. It can be seen that regulation up price is lower at hours between 5 and 9 in all cases with CAES. Dispatch results show CAES is in compression mode at those hours and can provide regulation up by stopping the compression of air. Case 4 has lowest regulation price because of two CAESs in the system.

Table 10 Emission coefficients of thermal units

<table>
<thead>
<tr>
<th>Unit</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
<th>G6</th>
<th>CAES</th>
</tr>
</thead>
<tbody>
<tr>
<td>emission coefficient (lbs/MBtu)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Fig. 7 System operation cost ($1000)

Fig. 8 Hourly regulation up price ($/MW)
Table 11 System operation cost ($)  

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>2 083 351</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1 912 516</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1 893 766</td>
</tr>
</tbody>
</table>

4.2 IEEE 118-bus system

A modified IEEE 118-bus test system is used to study the proposed model for day-ahead scheduling with wind integration and CAES. The system has 54 units and 186 branches. The system is divided into three zones. The peak load of 7300 MW occurs at hour 21. The system topology is given in [7, 33].

Three wind units and three CAESs are located on Buses 36, 77 and 69 consequently. The capacity of wind units, corresponding hourly profile and characteristic of CAESs are same as the one in eight-bus example.

The proposed scenarios for this study are:

- **Scenario 1:** Base case without wind and CAES.
- **Scenario 2:** With wind units.
- **Scenario 3:** Wind integrated with CAES.

The 118-bus system operation costs in Scenarios 1–3 are presented in Table 11. First, the SCUC solution with a daily dispatch cost of $2 083 351 is obtained without considering wind and CAES. The addition of wind power units to the base case reduces the operating costs by $170 834. The system operation cost decreases to $1 912 516 because of the wind power generation. The least cost occurs when CAES integrates with wind in Scenario 3. Detailed test case results are not presented in this paper because of space limits, but satisfactory results were obtained similar to the eight-bus test case.

5 Conclusions

An SCUC problem with integrating wind and CAES is presented in this paper. The case studies based on eight-bus and IEEE 118-bus systems demonstrated the effectiveness of the proposed model and formulation, and also the advantage of CAES. We observed that CAES can impact the peak-load reduction, system operating cost, emission, system reliability, commitment and dispatch of the units. Much of the benefits listed in this paper will depend on the MW size of the CAES and location. CAES is economical when the marginal cost of electricity varies more than the costs of storing and retrieving the energy plus the price of energy lost in the process.

The proposed model can be used for operation planning in the days ahead as well as the long-term planning of wind unit integrated with CAES. Future work will include modelling for wind uncertainty/intermittency in the developed SCUC formulation. In addition, including set of contingencies and additional constraints in this formulation will be future work.

6 References

7. Shahidehpour, M., Yamin, H., Li, Z.: ‘Market operations in electric power systems’ (John Wiley and Sons, 2002)