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Security-Constrained Unit Commitment Considering Large-Scale Compressed Air Energy Storage (CAES) Integrated With Wind Power Generation

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Abstract

Environmental concerns and depletion of nonrenewable resources has made great interest towards renewable energy resources. Cleanness and high potential are factors that caused fast growth of wind energy. However, the stochastic nature of wind energy makes the presence of energy storage systems (ESS) in wind integrated power systems, inevitable. Due to capability of being used in large-scale systems and the lower capital cost, compressed air energy storage (CAES) is one of the favorable storage systems. This paper proposes a model for security-constrained unit commitment (SCUC) with integration of large-scale CAES and wind generation. The SCUC problem is formulated as a mixed-integer linear program (MIP) in which a lossless dc representation of transmission network is used and it has been solved by CPLEX solver using General Algebraic Modeling System (GAMS) optimization package. The IEEE RTS 96-bus systems is used to validate the performance of the proposed method.

Keywords: mixed-integer linear program; security-constrained unit commitment (SCUC); compressed air energy storage (CAES)
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1. Introduction

Global warming, air pollution and green house phenomena are global climate concerns caused great struggle in exploiting renewable energy resources. Among renewable energy resources, many researchers have acknowledged the potential of wind energy and have been striving for ingenious ways to augment the utilization of wind power. Nevertheless, electricity generation from intermittent and erratic wind energy resources engenders new challenges such as power quality for customers and reliability issues in power system.

One of the proven solutions to deal with variability of wind energy is the usage of storage systems. Different kind of storage systems such as compressed air energy storage (CAES), pumped hydro-electric storage, hydrogen storage, batteries, flywheel, capacitors and super capacitors and super conducting magnetic storage have been introduced [1]. CAES systems and pumped storages have the capability of being used in large scale wind energy integration. It is concluded in [2] that CAES is the preferable technology than the pumped storage, due to the lower capital cost of CAES. CAES draws power in order to compress the air in the large-scale underground storages in the off-pick periods and then using this compressed air for power generation in the pick periods for operation cost minimization.

The size and complexity of electric power grid has augmented in recent years and because of difficulties in building new network substructures, many blackouts have been reported around the world [3]. Thus, In order to achieve economical, reliable and secure energy production in the power system, generation resources can be necessarily scheduled by unit commitment (UC). The emphasis of recent works is on security constrains for UC (SCUC) [4, 5] and the impact of renewable energies' uncertainty [6, 7]. The bases of SCUC are discussed in [8, 9]. The objective of SCUC is obtaining a UC schedule at minimum production cost with considering different unit and system constraints. The main complex SCUC problem has been decomposed into a master problem (UC) and network security check sub-problems as a simplification approach in [8, 10] so that the network variations are minimized.

In this paper, the SCUC problem is comprehensively formulated as a mixed-integer linear program in which a lossless dc representation of transmission network is used. Also, the optimization model is developed to determine the impact of wind integration and CAES facility on cost minimization. Since Generalized Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical problems and modeling linear, nonlinear and mixed-integer optimization problems, solvers in GAMS are used to deal with the proposed SCUC problem. The rest of the paper is organized as follows. In section II wind turbine and uncertainty is modelled. In section 3 a mathematical formulation of SCUC with CAES consideration is discussed. Section 4, 5 present the case study and simulation results, respectively. Finally, the conclusion is provided in section 6.

2. Wind Power Modeling and Uncertainty

Since the wind output power is an erratic quality, it's difficult to be determined. Generally, in many studies analyzing wind output power through wind velocity and using linear definition of output power of wind turbine generator to model the actual wind power has been proposed [11].

$$P_W = \begin{cases} 0 & , V_{WS} < V_{cutin} , V_{WS} > V_{cutout} \\ P_{WG\max} \times \left(\dfrac{V_{WS} - V_{cutin}}{V_{rated} - V_{cutin}} \right) & , V_{cutin} \le V_{WS} \le V_{rated} \\ P_{WG\max} & , V_{rated} \le V_{WS} \le V_{cutout} \end{cases} \quad (1)$$

Where P_{WGmax} is the maximum output power of wind turbine and $V_{cutin}, V_{rated}, V_{cutout}, V_{WS}$ are down cut speed, rated speed, up cut speed and semi-variable speed wind turbine, respectively.

In addition to average amount, wind speed forecasting always includes standard deviation because of prediction error. Weibull distribution function is a proper model for stochastic behavior of wind speed [12]. The wind speed is divided into scenario steps so that the probability of each scenario (φ_w) and the amount of corresponding wind speed (V_w) w-th scenario steps of wind can be calculated as in (2) and (3).

Where V_w^{max} and V_w^{min} are the minimum and maximum wind speed in one w of scenario steps.

Wind scenarios and probability used in this paper are presented in Table 1. Moreover, wind speeds data derived from NREL's Western wind dataset [13]. Each location is an artificial wind site with 10 aggregated Vestas V90-3MW wind turbines whose operation data is presented in Table 2.

$$\varphi_w = \int_{V_w^{min}}^{V_w^{max}} (\frac{\beta}{c}) \left(\frac{v}{c}\right)^{\beta-1} exp\left[-(\frac{v}{c})^{\beta}\right] \quad (2)$$

$$V_w = \frac{1}{\varphi_w} \times \int_{V_w^{min}}^{V_w^{max}} \left(v \times \frac{\beta}{c} \left(\frac{v}{c}\right)^{\beta-1} exp\left[-(\frac{v}{c})^{\beta}\right] \right) dv \quad (3)$$

Table.1.
Wind scenarios & Probabilities

Scenario	***Probability***	***Scenario***	***Probability***
1	0.022	6	0.150
2	0.158	7	0.086
3	0.101	8	0.009
4	0.240	9	0.124
5	0.101	10	0.009

Table.2.
Operational data for Vestas V90

Rated power	3000 kW
Cut-in wind speed	3.5 m/s
Rated wind speed	15 m/s
Cut-out wind speed	25 m/s
Re cut-in wind speed	20 m/s
Wind class	IEC IA/IIA
Operating temperature range standard turbine	-20˚C to 40˚C

3. Problem Formulation

The problem is formulated as a mixed-integer linear program in which a lossless dc representation of transmission network is used. If the dc representation of power flow is used, it may cause up to 5% error in line loadings which is justified in techno-economic and planning studies [14]. By evaluating losses a priori and including them in in the load, the error can be reduced [15]. First, the indices used in the formulations are introduced as follows:

- h Index to the piecewise linear segments of the cost curve of generating unit from 1 to H
- i Index to the set of generating units from 1 to I.
- j Index to the set of start-up cost of generating units from 1 to J.
- l Index to the set of transmission lines from 1 to L.
- b Index to the set of buses from 1 to B.
- t Index to the set of time periods in the optimization horizon, from 1 to T
- s Index to the scenarios from 1 to S
- k Index to the CAES units from 1 to K

The objective function for each hour of day is composed of the generation costs, $Cost_{th}(t,s)$ of all the generators i over all time periods t and operation cost of CAES, $Cost_c(t,s)$. It is worth noting that the operation cost of wind is negligible. The mathematical model of the proposed objective function is presented as

$$\sum_{t=1}^{T}\sum_{s=1}^{S}\mu_{\lambda}(s)\,[Cost_{th}(t,s)+cost_{c}(t,s)] \tag{4}$$

Where $\mu_{\lambda}(s)$ is the probability of s-th scenario. The generation cost of all generators can be divided into three parts of no-load generation cost, the variable generation cost and the start-up cost $suc_i(t,s)$ as expressed in (5).

$$Cost_{th}(t,s) = \sum_{i=1}^{I}\left[NLC_i.x_i(t)+\sum_{h=1}^{H}m_{i,h}.p_{i,h}(t,s)+suc_i(t)\right] \quad \forall t \le t, i \le I \tag{5}$$

The no-load cost, $NLC_i(\$)$, is multiplied by the unit on-off status. The piecewise linear cost curves are used for calculating the variable generation cost. The slop of segment m of generator i's cost curve, $m_{i,h}$, multiplies generation power of the same segment, $p_{i,h}(t,s)$ (MW). Moreover, the operating cost of CAES system is expressed as follows:

$$cost_c(t,s)=\sum_{k=1}^{K}\lambda_e(t,s)\times P_{c,p}\,(k,t,s) \tag{6}$$

Where $\lambda_e(t,s)$ is the estimated market price at time t (\$/MW h) and $P_{c,p}(k,t,s)$ is the consumed energy of k-th CAES at time t which is sold to the market in MW.

The optimization constrains are listed as below.

A) *Constrains on the binary variables:*

$$y_i(t_1)-z_i(t_1)=x_i(t_1)-p_{g_i}^{on-off} \quad \forall i \le I \tag{7}$$

$$y_i(t)-z_i(t)=x_i(t)-x_i(t-1), \forall\, 2 \le t \le T \tag{8}$$

$$y_i(t)+z_i(t) \le 1 \quad t \le T, i \le I \tag{9}$$

Equations (7)-(9) are the binary variables used for determining the state of generator i, where $x_i(t)$ is on-off status, $y_i(t)$ is the start-up status and $z_i(t)$ is the shut-down status. These variables are equal to 1 if generator i is producing energy; started up and shut-down at time period of t, respectively. Otherwise, they are 0. $p_{g_i}^{on-off}$ is the initial generator on-off status.

B) *Generator output constraints:*

$$p_i(t,s)=\sum_{h=1}^{H}p_{i,h}(t,s) \quad \forall t \le T, i \le I \tag{10}$$

$$p_i(t,s) \ge p_{g_i}^{min}.x_i(t) \quad \forall t \le T, i \le I \tag{11}$$

$$p_{i,h}(t,s) \le p_{g_{i,h}}^{max}.x_i(t) \ \forall t \le T, i \le I, h \le H \tag{12}$$

In constraint (10), the generator outputs, $p_i(t,s)$, is defined as the sum of the power produced on each segment of its curve, $p_{i,h}(t,s)$ at each scenario. The minimum limits ($p_{g_i}^{min}$) and maximum limits ($p_{g_{i,h}}^{max}$) on generator outputs, is expressed in (11) and (12).

C) *Generator up and down time:*

$$x_i(t)=p_{g_i}^{on-off} \quad \forall t \le LT_i^{u,min}+LT_i^{d,min}, i \le I \tag{13}$$

$$\sum_{tt=t-p_{g_{i,h}}^{u}+1}^{t} y_i(tt) \le x_i(t) \quad \forall t \ge LT_i^{u,min}, i \le I \tag{14}$$

$$x_i(t)+\sum_{tt=t-p_{g_{i,h}}^{u}+1}^{t} z_i(tt) \le 1 \quad \forall t \ge LT_i^{d,min}, i \le I \tag{15}$$

Constraint (13) sets on-off status for the first $LT_i^{u,min}$ or $L_i^{d,min}$ time periods to be equal to the on-off status of generator i, $p_{g_i}^{on-off}$, at $t=0$. $LT_i^{u,min}$ is equal to $max\left\{0,\min\left\{T,\left(p_{g_i}^{u}-\right.\right.\right.$ *pgiu,init.pgion−off* which is the number of periods that generator i has to be on at the beginning of the optimization horizon. Similarly, $LT_i^{d,min}$ is equal to: $max\left\{0,\min\left\{T,\left(p_{g_i}^{d}-\right.\right.\right.$ *pgid,init.(1−pgion−off)*, *pgiu* is the minimum up time of the generator i and $p_{g_i}^{d}$ is its minimum down time. $p_{g_i}^{u,init}$ denotes the time that generator i has been up before the first time period, while $p_{g_i}^{d,init}$ is the time that generator i has been down before the first time period. The minimum up and down time for the remaining time periods are imposed by constraints (14) and (15).

D) *Start-up costs:*

$$\sum_{j=1}^{J}\omega_{i,j}=y_i(t) \quad \forall t \le T, i \le I \tag{16}$$

$$\omega_{i,j}(t) \le \sum_{tt=suc_{i,j}^{lim}}^{min\{t-1,suc_{i,j+1}^{lim}-1\}} z_i(t-tt)+ 1\$\left\{j \le J-1 \ \wedge \ suc_{i,j}^{lim} \le p_{g_i}^{d,init}+t-1<\right.$$
suci,jlim+1\$j=J∧suci,jlim≤pgid,init+t−1
$$\forall t \le T, i \le I, j \le J \tag{17}$$

$$suc_i(t)=\sum_{j=1}^{J}\omega_{i,j}(t).suc_{i,j}^{cost} \quad \forall t \le T, i \le I \tag{18}$$

Binary variable $\omega_{i,j}(t)$ equals 1 if generator i is started at time period t after being off for j time periods, otherwise it is 0. Constraint (16) enforces one j element of $\omega_{i,j}(t)$ to be equal to 1 if a generator is started at time period t. Depending on the number of time periods a generator has been off, the j element that will be set to 1 is determined by Eq. (17). $suc_{i,j}^{lim}$ stands for the time limits of each segment of the stepwise j-segments start-up cost curve of generator i. The first term on the right-hand side of Eq. (17) expresses the appropriate j element to be equal to 1 if a generator was last shut down within the optimization horizon. The second term equals 1 if a generator was last shut down up to J time periods before the current one, considering the down time prior to the optimization horizon. The third term equals 1 if a generator has been shut down for J or more time periods, considering the down time prior to the optimization horizon. Being shut down for J or more time periods gives rise to the highest start-up cost. By multiplying the binary variable $\omega_{i,j}(t)$ with the corresponding stepwise start-up cost values $suc_{i,j}^{cost}$, the actual start-up cost is derived in (18).

E) *Ramping constraints:*

$$-RD_i \leq p_i(t_1,s) - p_i^0 \quad \forall i \leq I \tag{19}$$

$$RU_i \geq p_i(t_1,s) - p_i^0 \quad \forall i \leq I \tag{20}$$

$$-RD_i \leq p_i(t,s) - p_i(t-1,s) \quad \forall 2 \leq t \leq T \tag{21}$$

$$RU_i \leq p_i(t,s) - p_i(t-1,s) \quad \forall 2 \leq t \leq T \tag{22}$$

The ramp down and ramp up constraints for the first time period for generator output at $t = 0$, p_i^0, are imposed by (19) and (20), respectively. Equations (21) and (22) express the ramping constrains for the remaining time periods.

F) CAES constraints*:*

$$V^{inj}(k,t,s) = \alpha^{inj}(k)\,.\,P_{c,p}(k,t,s) \quad \forall t \leq T, k \leq K \tag{23}$$

$$P_{c,s}(k,t,s) = \alpha^{p}(k)\,.\,V^{p}(k,t,s) \quad \forall t \leq T, k \leq K \tag{24}$$

$$V_{min}^{inj}(k).u^{inj}(k,t,s) \leq V^{inj}(k,t,s) \leq V_{max}^{inj}(k).u^{inj}(k,t,s) \tag{25}$$

$$V_{min}^{p}(k)\,.u^{p}(k,t,s) \leq V^{p}(k,t,s) \leq V_{max}^{p}(k)\,.u^{p}(k,t,s) \tag{26}$$

$$u^{p}(k,t,s) + u^{inj}(k,t,s) \leq 1 \tag{27}$$

$$A(k,t+1,s) = A(k,t,s) + V^{inj}(k,t,s) - V^{p}(k,t,s) \tag{28}$$

$$A^{min}(k) \leq A(k,t,s) \leq A^{max}(k) \tag{29}$$

In [9] the constraints related to CAES are presented in (23)-(29). The amount of injected air into storage in mathematical model is enforced by constraint (23), where $P_{c,p}(k,t,s)$ is the consumed energy of k-th CAES at time t in scenario s for compressing and injecting air (MW), $V^{inj}(k,t,s)$ is the amount of injected air into k-th CAES (MW/h) and $\alpha^{inj}(k)$ is the yield of injected power to k-th CAES. Equation (24) expresses the amount of energy produced by CAES $P_{c,s}(k,t,s)$, where $\alpha^{p}(k)$ is the yield of produced power from k-th CAES and $V^{p}(k,t,s)$ is the amount of pumping air into the combustion chamber by k-th CAES (MW/h). The efficiency factors α^{inj}, α^{p} for compression and generation are 95%. Equation (25) and (26) present the mathematical model of the air stored in storage and then pumped from the storage to the combustion chamber, where $V_{min}^{inj}(k)$ and $V_{max}^{inj}(k)$ are the lowest and highest amount of injected air to the k-th CAES, $V_{min}^{p}(k)$ and $V_{max}^{p}(k)$ are the lowest and highest amount of pumping air into the combustion chamber by k-th CAES, $u^{inj}(k,t,s)$ is a binary variable which is equal to 1 if air is injected by the k-th CAES at time t in scenario s, otherwise it is 0, and $u^{p}(k,t,s)$ is another binary variable which is equal to 1 if air is pumped by the k-th CAES at time t in scenario s, otherwise it is 0. CAES operates in storage mode (storing air inside the storage) or in pumping mode (pumping air from storage into the combustion chamber. Thus, constraint (27) is used for preventing CAES from simultaneous operation in the above two modes. Constraint (28) is the dynamic model of energy for CAES in any time. The last constraint in Eq. (29) is the limitations of the storage tank to store the air, where $A(k,t,s)$ is the level of stored energy in k-th CAES at time t in scenario s and $A^{min}(k)$ and $A^{max}(k)$ are the minimum and maximum energy stored k-th CAES (MWh). The market price per hour of system is presented in Fig. 1.

7) Transmission constraint:

$$\sum_{i=1|i\in B}^{I} p_i(t,s) + \sum_{\omega=1|\omega\in B}^{W}\big(a\omega_{\omega}(t,s) - \tag{30}$$
cωωt,s−b,n∈L|n>b
Bbnθbt,s−θnt,s+b,n∈L|n<b
Bnbθnt,s−θbt,s+Pcst,s=loadt,s+Pc,pt,s

$$-flow_{nm}^{max} \leq B_{bn}\big(\theta_b(t,s) - \theta_n(t,s)\big) \leq flow_{nm}^{max}\,, \forall t \leq T, \{b,n\} \in L \tag{31}$$

$$-\pi \leq \theta_b(t,s) \leq \pi \quad \forall t \leq T, b \leq B \backslash b{:}\,ref\ bus \tag{32}$$

$$\theta_b(t,s) = 0 \quad \forall t \leq T, b{:}\,ref\ bus \tag{33}$$

The power balance is presented by Eq. (30). $a\omega_{\omega}(t,s)$ is the available wind farm power output at s-th scenario, whereas $c\omega_{\omega}(t,s)$is the curtailed wind output power at s-th scenario which is a positive variable. B_{bn} denotes the admittance of the line connecting nodes b and n (N). And, $\theta_b(t,s)$ is the voltage angle at bus b (rad). The limit on the line flow $flow_{nm}^{max}$ is imposed by constraint (31). Constraints (32) and (33) limit the angles of voltage and set the reference bus.

4. Case Study

The modified version of the IEEE RTS-96 with an hourly time step was used for testing the proposed approach. Cost curves and condition prior to the optimization horizon are chosen based on generator data in [16]. 19 wind farms with total installed capacity of 6900 MW and penetration of 10% have been added to the available 73-bus, 96-generator, 51-load and 120-line system. The line-ratings have been reduced to 80% of their original values to similitude ERCOT, where the west part of it includes most of the wind generation. Also, the 24-hour system load is presented in Fig 2. It is worth noting that according to the most favorable storage locations determined for IEEE RTS-96 in [17], one CAES is located in bus named b121.the assumed CAES characteristics are presented in Table 3.

5. Results and Discussions

To investigate the impact of wind energy and CAES on SCUC problem, four case studies are used in numerical simulation. These case studies will be discussed and evaluated below.

Case study 1: Deterministic SCUC without wind and without CAES

In this case wind energy resources and CAES system are not considered. Deterministic SCUC is solved and the commitment of units is determined. The commitment schedule is depicted in Table 4 where 1/0 presents the hourly on/off status of units. As it is obvious the less expensive units are always committed, while the most expensive units are always off. In this case the daily generation dispatch cost is 2 689 827.678 $.

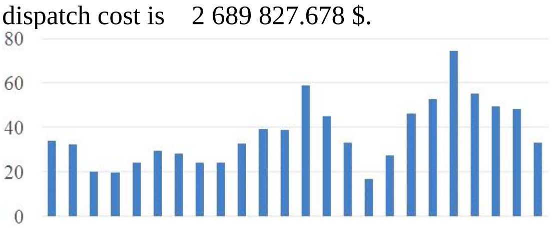

Fig. 1. 24-hour system load

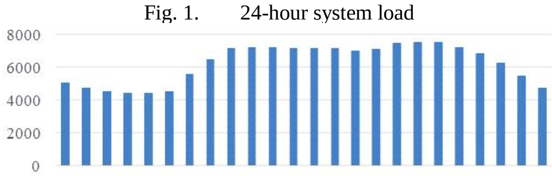

Fig. 2. 24-hour system load

Table.3.
CAES characteristics

unit	Bus	A_{min}	A_{max}	V_{min}^{inj}	V_{max}^{inj}	V_{min}^{p}	V_{min}^{p}
CAES	b121	50	200	5	50	5	50

Case study 2: Deterministic SCUC with wind and without CAES

In case 2 the Deterministic SCUC is studied with existence of wind generation and without CAES system to show to observe the positive impact of wind generation on cost reduction. In this case, as shown in Table 5, the daily generation cost is reduced by 14.63% and reached 2 296 288.712 $.Also the bold 1/0 shows that with integration of wind energy some costly units are getting off prior to case 1.

Case study 3: Deterministic SCUC with wind and with CAES

A CAES unit is located in bus b121 so that the impact of CAES can be observed. The maximum output power of CAES is 50MW. It is worth noting that the CAES is coupled with wind resources. Thus, as shown in left-side part of the Table 8, CAES is deriving energy just in T_4, T_5 and T_6 from the grid for air compression. The power produced by CAES for supplying the loads ranges from 4.75 MW to 47.5 MW during 24 hours. The operation schedule of this case is presented in Table 6. The daily generation dispatch cost is favourably reduced to 1 942 225.412 $ in presence of CAES.

Case study 4: Stochastic SCUC with wind and with CAES

In this case the stochastic SCUC with wind and CAES consideration is carried out. The corresponding output power and consumed power of CAES are presented in right-side part of Table 8, and Table 7 shows the commitment schedule of units. The daily generation dispatch cost of stochastic SCUC 1 948 008.759 $ which is higher than that of deterministic SCUC because of stochastic nature of wind energy. Figure (3) shows the amount of wind curtailment at each windfarm in 2 cases, curtailment without considering CAES and with CAES. In case 3 CAES is located at bus b121 close to the windfarm 8 and has the lowest wind curtailment. These amounts of curtailment directly depend on the size of the storage located close to the wind farms. In fact, the larger storage size is, the lower wind power loss becomes.

6. Conclusion

A SCUC problem with integration of CAES and wind energy has been solved by CPLEX solver using GAMS in this paper. It has been formulated as a mixed-integer linear program where a lossless dc representation of transmission network has been used. Four case studies based on IEEE RTS 96-bus system have been evaluated. Simulation results also show that CAES has impacts on decreasing system operation cost, commitment of units and decreasing wind curtailment and also demonstrate that the combination of wind and CAES improves the performance of wind integrated power system. By comparing four cases, it can be found out that the case study with both wind and CAES, is more beneficial than other cases. The advantages discussed in this paper also demonstrate that the location and MW size of CAES is very important. The larger storage size becomes the lower wind power loss, the lower system operation cost and the higher profit is obtained.

Table.4.
Deterministic SCUC without wind and without CAES

Total Operation Cost = 2689827.678 $					
Unit	24 Hour scheduling	Unit	24 Hour scheduling	Unit	24 Hour scheduling
G1	000000 000000 000000 000000	G33	000000 000000 000000 000000	G65	001010 000000 000000 000000
G2	000000 000000 000000 000000	G34	000000 000000 000000 000000	G66	000000 000000 000000 000000
G3	110000 111111 111111 111110	G35	110000 111111 111111 111100	G67	110000 011111 111111 111100
G4	000000 111111 111111 111110	G36	000000 011111 111111 111110	G68	111000 011111 111111 111100
G5	000000 000000 000000 000000	G37	000000 000000 000000 000000	G69	000000 000000 000000 000000
G6	000000 000100 000010 000000	G38	000000 000000 000000 000000	G70	000000 000000 000000 000000
G7	111000 111111 111111 111110	G39	000000 011111 111111 111110	G71	000000 011111 111111 111100
G8	000000 111111 111111 111110	G40	000000 111111 111111 111110	G72	000000 011111 111111 111100
G9	111111 111111 111111 111111	G41	111001 111111 111111 111111	G73	111000 111111 111111 111110
G10	111111 111111 111111 111111	G42	111100 111111 111111 111111	G74	111000 111111 111111 111110
G11	111111 111111 111111 111111	G43	100001 111111 111111 111111	G75	111001 111111 111111 111110
G12	111111 111111 111111 111111	G44	111111 111111 111111 111111	G76	111111 111111 111111 111111
G13	111111 111111 111111 111111	G45	111111 111111 111111 111111	G77	111111 111111 111111 111111
G14	001111 111111 111111 111111	G46	111111 111111 111111 111111	G78	111111 111111 111111 111111
G15	000000 000000 000000 000000	G47	000000 000000 000000 000000	G79	000000 000000 000000 000000
G16	000000 000000 000010 000000	G48	000000 000000 000000 000000	G80	000000 000000 000000 000000
G17	000000 000000 000000 000000	G49	000000 000000 000000 000000	G81	000000 000000 000000 000000
G18	000000 000000 000000 000000	G50	000000 000000 000000 000000	G82	000000 000000 000000 000000
G19	000000 000000 000000 000000	G51	000000 000000 000000 000000	G83	000000 000000 000000 000000
G20	110000 111111 111111 111000	G52	100000 111111 000000 000000	G84	100000 111111 111111 111000
G21	110000 111111 111111 111100	G53	110000 111111 111111 111000	G85	100000 000000 000000 000000
G22	111111 111111 111111 111111	G54	111111 111111 111111 111111	G86	111111 111111 111111 111111
G23	111111 111111 111111 111111	G55	111111 111111 111111 111111	G87	111111 111111 111111 111111
G24	000000 000000 000000 000000	G56	000000 000000 000000 000000	G88	000000 000000 000000 000000
G25	000000 000000 000000 000000	G57	000000 000000 000000 000000	G89	000000 000000 000000 000000
G26	000000 000000 000000 000000	G58	000000 000000 000000 000000	G90	000000 000000 000000 000000
G27	000000 001100 000000 000000	G59	000000 000000 000000 000000	G91	000000 000000 000111 100000
G28	000000 000000 000000 000000	G60	000000 000000 000000 000000	G92	000000 000000 000000 000000
G29	000000 000000 000000 000000	G61	000000 000000 000000 000000	G93	000000 000000 000000 000000
G30	110000 001111 111111 111100	G62	110000 111111 111111 111000	G94	110000 111111 111111 111000
G31	000000 000011 000000 000000	G63	000000 000000 000011 111100	G95	000000 000000 000111 110000
G32	000000 000000 000000 000000	G64	000000 000000 000000 000000	G96	000000 000000 000000 000000

Table.5.
Deterministic SCUC with wind and without CAES

Total Operation Cost = 2296288.712 $					
Unit	24 Hour scheduling	Unit	24 Hour scheduling	Unit	24 Hour scheduling
G1	000000 000000 000000 000000	G33	000000 000000 000000 000000	G65	000000 000000 000000 000000
G2	000000 000000 000000 000000	G34	000000 000000 000000 000000	G66	000000 000000 000000 000000
G3	110000 111111 111111 111100	G35	110000 011111 111111 111000	G67	110000 011111 111111 111000
G4	000000 111111 111111 111100	G36	000000 011111 111111 111000	G68	000000 011111 111111 110000
G5	000000 000000 000000 000000	G37	000000 000000 000000 000000	G69	000000 000000 000000 000000
G6	000000 000000 000010 000000	G38	000000 000000 000000 000000	G70	000000 000000 000000 000000
G7	000000 111111 111111 111100	G39	000000 011111 111111 111000	G71	000000 011111 111111 111000
G8	000000 111111 111111 111100	G40	000000 011111 111111 111100	G72	000000 011111 111111 111000
G9	111100 111111 111111 111110	G41	111001 111111 111111 111110	G73	111000 111111 111111 111110
G10	111001 111111 111111 111110	G42	111001 111111 111111 111110	G74	110000 111111 111111 111100
G11	111111 111111 111111 111110	G43	111001 111111 111111 111110	G75	111001 111111 111111 111110
G12	111111 111111 111111 111111	G44	111111 111111 111111 111111	G76	111111 111111 111111 111111
G13	111111 111111 111111 111111	G45	111111 111111 111111 111111	G77	111111 111111 111111 111111
G14	000111 111111 111111 111111	G46	111111 111111 111111 111111	G78	111111 111111 111111 111111
G15	000000 000000 000000 000000	G47	000000 000000 000000 000000	G79	000000 000000 000000 000000
G16	000000 000000 000010 000000	G48	000000 000000 000000 000000	G80	000000 000000 000000 000000
G17	000000 000000 000000 000000	G49	000000 000000 000000 000000	G81	000000 000000 000000 000000
G18	000000 000000 000000 000000	G50	000000 000000 000000 000000	G82	000000 000000 000000 000000
G19	000000 000000 000000 000000	G51	000000 000000 000000 000000	G83	000000 000000 000000 000000
G20	100000 000000 000011 111000	G52	100000 000000 000000 000000	G84	100000 000000 000000 000000
G21	100000 000000 000000 000000	G53	100000 000000 000000 000000	G85	100000 000000 000000 000000
G22	111111 111111 111111 111111	G54	111111 111111 111111 111111	G86	111111 111111 111111 111111
G23	111111 111111 111111 111111	G55	111111 111111 111111 111111	G87	111111 111111 111111 111111
G24	000000 000000 000000 000000	G56	000000 000000 000000 000000	G88	000000 000000 000000 000000
G25	000000 000000 000000 000000	G57	000000 000000 000000 000000	G89	000000 000000 000000 000000
G26	000000 000000 000000 000000	G58	000000 000000 000000 000000	G90	000000 000000 000000 000000
G27	000000 000000 000000 000000	G59	000000 000000 000000 000000	G91	000000 000000 000111 100000
G28	000000 001100 000000 000000	G60	000000 000000 000000 000000	G92	000000 000000 000000 000000
G29	000000 000000 000000 000000	G61	000000 000000 000000 000000	G93	000000 000000 000000 000000
G30	110000 111111 111111 110000	G62	110000 111111 000111 110000	G94	110000 111111 111111 110000
G31	000000 111111 111111 110000	G63	000000 000000 000000 000000	G95	000000 000000 000000 000000
G32	000000 000000 000000 000000	G64	000000 000000 000000 000000	G96	000000 000000 000000 000000

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Table.6.
Deterministic SCUC with wind and with CAES

Total Operation Cost = 1942225.412 $					
Unit	24 Hour scheduling	Unit	24 Hour scheduling	Unit	24 Hour scheduling
G1	000000 000000 000000 000000	G33	000000 000000 000000 000000	G65	000000 000000 000000 000000
G2	000000 000000 000000 000000	G34	000000 000000 000000 000000	G66	000000 000000 000000 000000
G3	000000 111111 111111 111100	G35	000000 111111 111111 111110	G67	000000 000111 000000 000000
G4	000000 001110 011111 111100	G36	000000 011111 111111 100000	G68	000000 000000 000000 111110
G5	000000 000000 000000 000000	G37	000000 000000 000000 000000	G69	000000 000000 000000 000000
G6	000000 000000 000010 000000	G38	000000 000000 000000 000000	G70	000000 000000 000000 000000
G7	000000 011111 111111 111110	G39	000000 111111 111111 110000	G71	000000 011111 100001 110000
G8	000000 011111 111111 110000	G40	000000 011111 111111 111000	G72	000000 000011 111111 100000
G9	111100 111111 111111 111110	G41	111111 111111 111111 111110	G73	111000 111111 111111 111110
G10	110011 111111 111111 111110	G42	111111 111111 111111 111110	G74	111111 111111 111111 111100
G11	111000 111111 111111 111110	G43	111100 111111 111111 111110	G75	111000 111111 111111 111110
G12	111111 111111 111111 111110	G44	111111 111111 111111 111110	G76	111111 111111 111111 111110
G13	111111 111111 111111 111110	G45	111111 111111 111111 111110	G77	111111 111111 111111 111110
G14	000111 111111 111111 111110	G46	011111 111111 111111 111110	G78	011111 111111 111111 111110
G15	000000 000000 000000 000000	G47	000000 000000 000000 000000	G79	000000 000000 000000 000000
G16	000000 000000 000000 000000	G48	000000 000000 000000 000000	G80	000000 000000 000000 000000
G17	000000 000000 000000 000000	G49	000000 000000 000000 000000	G81	000000 000000 000000 000000
G18	000000 000000 000000 000000	G50	000000 000000 000000 000000	G82	000000 000000 000000 000000
G19	000000 000000 000000 000000	G51	000000 000000 000000 000000	G83	000000 000000 000000 000000
G20	100000 000000 000000 000000	G52	100000 000000 000000 000000	G84	100000 000000 000000 000000
G21	100000 000000 000000 000000	G53	100000 000000 000000 000000	G85	100000 000000 000000 000000
G22	111111 111111 111111 111111	G54	111111 111111 111111 111111	G86	111111 111111 111111 111111
G23	111111 111111 111111 111111	G55	111111 111111 111111 111111	G87	111111 111111 111111 111111
G24	000000 000000 000000 000000	G56	000000 000000 000000 000000	G88	000000 000000 000000 000000
G25	000000 000000 000000 000000	G57	000000 000000 000000 000000	G89	000000 000000 000000 000000
G26	000000 000000 000000 000000	G58	000000 000000 000000 000000	G90	000000 000000 000000 000000
G27	000000 000000 000000 000000	G59	000000 000000 000000 000000	G91	000000 000000 000000 000000
G28	000000 000000 000000 000000	G60	000000 000000 000000 000000	G92	000000 000000 000000 000000
G29	000000 000000 000000 000000	G61	000000 000000 000000 000000	G93	000000 000000 000000 000000
G30	100000 000000 000000 000000	G62	100000 000000 000000 000000	G94	100000 000000 000000 000000
G31	000000 000000 000000 000000	G63	000000 000000 000000 000000	G95	000000 000000 000000 000000
G32	000000 000000 000000 000000	G64	000000 000000 000000 000000	G96	000000 000000 000000 000000

Table.7.
Stochastic SCUC with wind and CAES

Total Operation Cost = 1948008.759 $					
Unit	24 Hour scheduling	Unit	24 Hour scheduling	Unit	24 Hour scheduling
G1	000000 000000 000000 000000	G33	000000 000000 000000 000000	G65	000000 000000 000000 000000
G2	000000 000000 000000 000000	G34	000000 000000 000000 000000	G66	000000 000000 000000 000000
G3	000000 111111 111111 111110	G35	000001 111111 111111 110000	G67	000000 000111 000000 011100
G4	000000 001111 111111 111100	G36	000000 011111 111111 100000	G68	000000 111111 111111 111110
G5	000000 000000 000000 000000	G37	000000 000000 000000 000000	G69	000000 000000 000000 000000
G6	000000 000000 000010 000000	G38	000000 000000 000000 000000	G70	000000 000000 000000 000000
G7	000001 111111 111111 111110	G39	000000 111111 111111 111110	G71	000000 011111 100001 110000
G8	000000 011111 111111 111110	G40	000000 011111 111111 111000	G72	000011 111111 111111 110000
G9	111111 111111 111111 111110	G41	111111 111111 111111 111110	G73	111001 111111 111111 111110
G10	110011 111111 111111 111110	G42	111111 111111 111111 111110	G74	111111 111111 111111 111100
G11	110011 111111 111111 111110	G43	111100 111111 111111 111110	G75	111000 011111 111111 111110
G12	111111 111111 111111 111110	G44	111111 111111 111111 111110	G76	111111 111111 111111 111110
G13	111111 111111 111111 111110	G45	111111 111111 111111 111110	G77	111111 111111 111111 111110
G14	000111 111111 111111 111110	G46	011111 111111 111111 111110	G78	011111 111111 111111 111110
G15	000000 000000 000000 000000	G47	000000 000000 000000 000000	G79	000000 000000 000000 000000
G16	000000 000000 000000 000000	G48	000000 000000 000000 000000	G80	000000 000000 000000 000000
G17	000000 000000 000000 000000	G49	000000 000000 000000 000000	G81	000000 000000 000000 000000
G18	000000 000000 000000 000000	G50	000000 000000 000000 000000	G82	000000 000000 000000 000000
G19	000000 000000 000000 000000	G51	000000 000000 000000 000000	G83	000000 000000 000000 000000
G20	100000 000000 000000 000000	G52	100000 000000 000000 000000	G84	100000 000000 000000 000000
G21	100000 000000 000000 000000	G53	100000 000000 000000 000000	G85	100000 000000 000000 000000
G22	111111 111111 111111 111111	G54	111111 111111 111111 111111	G86	111111 111111 111111 111111
G23	111111 111111 111111 111111	G55	111111 111111 111111 111111	G87	111111 111111 111111 111111
G24	000000 000000 000000 000000	G56	000000 000000 000000 000000	G88	000000 000000 000000 000000
G25	000000 000000 000000 000000	G57	000000 000000 000000 000000	G89	000000 000000 000000 000000
G26	000000 000000 000000 000000	G58	000000 000000 000000 000000	G90	000000 000000 000000 000000
G27	000000 000000 000000 000000	G59	000000 000000 000000 000000	G91	000000 000000 000000 000000
G28	000000 000000 000000 000000	G60	000000 000000 000000 000000	G92	000000 000000 000000 000000
G29	000000 000000 000000 000000	G61	000000 000000 000000 000000	G93	000000 000000 000000 000000
G30	100000 000000 000000 000000	G62	100000 000000 000000 000000	G94	100000 000000 000000 000000
G31	000000 000000 000000 000000	G63	000000 000000 000000 000000	G95	000000 000000 000000 000000
G32	000000 000000 000000 000000	G64	000000 000000 000000 000000	G96	000000 000000 000000 000000

Table.8.
Output power and consumed power of CAES

	Case 3		*Case 4*	
Hour	P_{cs}	P_{cp}	P_{cs}	P_{cp}
T1	34.379	0	34.413	0
T2	14.566	0	16.441	0
T3	4.750	0	4.75	0
T4	0	16.105	0	16.945
T5	0	17.837	0	18.019
T6	0	18.513	0	21.383
T7	0	0	0	0
T8	6.755	0	6.237	0
T9	12.337	0	11.930	0
T10	11.350	0	12.367	0
T11	9.611	0	11.547	0
T12	9.281	0	10.653	0
T13	8.503	0	9.851	0
T14	9.590	0	9.256	0
T15	6.318	0	6.1	0
T16	6.043	0	5.469	0
T17	10.443	0	9.792	0
T18	10.568	0	10.515	0
T19	10.331	0	10.732	0
T20	7.276	0	7.998	0
T21	4.895	0	4.750	0
T22	0	0	0	0
T23	14.181	0	12.524	0
T24	47.5	0	47.5	0

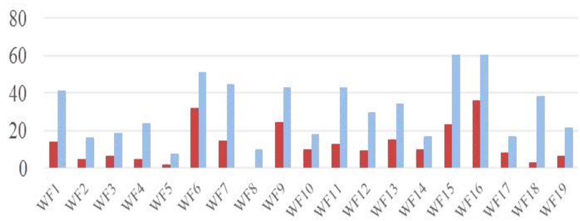

Fig. 3. Wind curtailment of WindFarms

7. Conclusion

A SCUC problem with integration of CAES and wind energy has been solved by CPLEX solver using GAMS in this paper. It has been formulated as a mixed-integer linear program where a lossless dc representation of transmission network has been used. Four case studies based on IEEE RTS 96-bus system have been evaluated. Simulation results also show that CAES has impacts on decreasing system operation cost, commitment of units and decreasing wind curtailment and also demonstrate that the combination of wind and CAES improves the performance of wind integrated power system. By comparing four cases, it can be found out that the case study with both wind and CAES, is more beneficial than other cases. The advantages discussed in this paper also demonstrate that the location and MW size of CAES is very important. The larger storage size becomes the lower wind power loss, the lower system operation cost and the higher profit is obtained.

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