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Unit Commitment in Presence of Wind Power Plants and Energy Storage

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Abstract

As renewable energy increasingly penetrates into power grid systems, new challenges arise for system operators to keep the systems reliable under uncertain circumstances, while ensuring high utilization of renewable energy. This paper presents unit commitment (UC) which takes into account the volatility of wind power generation. The UC problem is solved with the forecasted intermittent wind power generation and possible scenarios are simulated for representing the wind power volatility. The iterative process between the commitment problem and the economic dispatch(ED) problem will continue until we find the optimum mode of committing the units. Furthermore we have considered a hydro pump storage (HPS) unit to be a part of operating system in order to mitigating wind power forecasting errors and peak shaving. Numerical simulations indicate the effectiveness of the proposed UC for managing the security of power system operation by taking into account the intermittency and volatility of wind power generation.

Keywords: Unit Commitment, Economic Dispatch, Wind Power, Hydro Pump Storage Unit, Mont Carlo Simulation.

Nomenclatures

Index	
NG	Number of thermal units
NW	Number of wind units
NH	Number of pump storage units
NS	Number of scenarios
i	Power generation unit index
s	Scenario index
t	Time index
T	Time horizon
Binary Variables	
$I_{i,t}$	Commitment status of unit i at time t
$Y_{i,t}$	If unit i starts up at time t , is equal to 1
$S_{i,t}$	If unit i shuts down at time t , is equal to 1
IGH_t	HPS generating mode decision variable
IPH_t	HPS pumping mode decision variable
IIH_t	HPS inactive mode decision variable

Parameters	
$SU_{i,t}$	Startup cost of unit i at time t
$SD_{i,t}$	Shutdown cost of unit i at time t
$P_{i,min}$	Lower limit of real power generation of unit i
$P_{i,max}$	Upper limit of real power generation of unit i
RU_i	Ramp up rate of unit i
RD_i	Ramp down rate of unit i
Z_{begin}	Initial water reserve inventory of HPS
Z_{last}	Target water reserve inventory of HPS
$V_{h,max}$	Upper limit of reservoir volume in HPS
$V_{h,min}$	Lower limit of reservoir volume in HPS
A_1	Efficiency of pumping cycle of HPS
A_2	Efficiency of generating cycle of HPS
$L_{h,t}^{in}$	Lower limit of consumed power by HPS
$U_{h,t}^{in}$	Upper limit of consumed power by HPS
$L_{h,t}^{out}$	Lower limit of generated power by HPS
$U_{h,t}^{out}$	Upper limit of generated power by HPS
$SGC_{h,t}$	Srarting to generate , cost of HPS
$SPC_{h,t}$	Starting to pump , cost of HPS

T_i^{on}	Minimum up time of unit i
T_i^{off}	Minimum down time of unit i

Variables

$P_{i,t}$	Generation of unit i at time t
$P^{s}_{w,i,t}$	Generation of wind unit i at time t in scenario s
$P^{in}_{h,i,t}$	Absorbed power by HPS i at time t
$P^{out}_{h,i,t}$	Generated power by HPS i at time t
D_t^s	Demand at time t in scenario s
$R_{s,i,t}$	Spining reserve prepeared by unit i at time t
$R_{s,t}$	System spinning reserve requirement at time t
Z_t	Water reserve inventory at time t
$V_{h,t}$	Water volume in HPS at time t
$X^{on}_{i,t}$	Operating duration of unit i at time t
$X^{off}_{i,t}$	Shutdown duration at time t

Function

$FC_{i,t}$	Generating cost of thermal unit i at time t

1. Introduction

Wind energy has become increasingly popular across the globe. It is reported by the Global Wind Energy Council (GWEC) that global wind energy installations rose by 11 531 MW in 2005, which represent an annual increase of 40.5% [1]. Such figures demonstrate the prosperous future of wind power development. However, the intermittent and volatile nature of wind power generation may impact power system characteristics such as voltages, frequency and generation adequacy which can potentially increase the vulnerability of power systems. Intermittency refers to the unavailability of wind for an extended period and volatility refers to the smaller and hourly fluctuations of wind within its intermittent characteristics. The cumulative wind power (representing several wind farms) in a power system might not be intermittent. However, the power output of a single wind farm could be intermittent within a 24-h period. The intermittency of individual wind farms is considered in the proposed UC in order to ensure that prevailing constraints are satisfied.

There are several techniques for predicting the quantity of intermittent wind power [2], [3].Wind forecasting is conducted by simulation, statistical method, or a combination of the two. The simulation method is based on a large number of wind scenarios and starts by a numerical weather prediction (NWP) followed by local wind pattern predictions using analytical methods. The statistical method also starts from NWP followed by statistical, artificial neural network, or fuzzy logic methods instead of analytical methods for calculating the hourly quantity of intermittent wind power, in which large data sets are needed and spikes in wind data are hard to predict [4]. Although wind power is predictable to a limited extent, it cannot be forecasted with 100% accuracy for dispatching purposes. Hence, it is possible that the actual wind power would be different from its forecasted value. The uncertainty is characterized in this paper by considering the volatility in multiple scenarios.

The wind power forecasting and associated forecasting accuracy issues are important in analyzing the impact of wind power on power system operation. However, a complete discussion on wind speed, wind forecast, and wind power data analyses is beyond the scope of this paper, and deserves another full paper. Furthermore, the modeling of load forecasting error (load profile) is also performed in this work . Other uncertainties such as the modeling of generation and transmission outages are also important subjects for power system operation which are beyond the scope of this paper.

Wind farms could be managed by utility companies in which the real-time on/off status of non-wind units would be decided based on the hourly load behavior and the availability of intermittent wind power. However, in certain parts of the United States, the intermittency of wind could amount to several hundred megawatts in a matter of hours. Likewise, the volatility of wind power could have a tremendous impact on power system operations which poses new challenges for the electricity market management. Control room operators and ISOs in competitive electricity markets apply optimization methods for managing the security of the system while utilizing the merits of wind power generation [5]–[7].

In [8] the impact of intermittent wind generation on the operations of the Tennessee Valley Authority (TVA) power system is investigated and the operations of the TVA power system are outlined. In reference [9] authors have presented a new method for solving efficiently a large scale optimal unit commitment problem that was included three types of units (i) usual thermal units (ii) fuel constrained thermal units and (iii) pumped storage hydro units . The solution method in this paper uses a lagrangian relaxation. A new simulation method that could fully assess the impacts of large-scale wind power on system operations from cost, reliability, and environmental perspectives was introduced in [10]. For coordinating the wind and thermal generation scheduling problem a hybrid approach of combining branch and bound algorithm with a dynamic programming algorithm was developed in [11]. In [12] a security constrained unit commitment (SCUC) algorithm which takes into account the volatility of wind power generation is proposed. A stochastic cost model and a solution technique for optimal scheduling of the generators in a wind integrated power system considering the demand and wind generation uncertainties is presented in [13]. In [14] the effects of stochastic wind and load on the unit commitment and dispatch of power systems with high levels of wind power is examined and showed that stochastic optimization results in less production cost and better performing schedules than deterministic optimization. A computational framework for integrating the state-of-the-art numerical weather prediction (NWP) model in stochastic UC/ED formulations is proposed in [15] that accounts for wind power uncertainty. In [16] authors have presented an efficient formulation of the stochastic unit commitment problem that is designed for use in scheduling simulations of single-bus power systems. A robust optimization approach for accommodating wind output uncertainty is proposed in [17] that aims to providing a robust unit commitment schedule for the thermal generators in the day ahead market that minimizes the total cost under the worst wind power scenario. In [18] a stochastic dynamic programming approach to unit commitment and dispatch has proposed that minimizes the operating cost by making optimal unit commitment, dispatch and storage decisions in the face of uncertain wind generation. A novel approach to the security constrained unit commitment with uncertain wind power generation is presented in [19] that it's goal is to solve the problem considering multiple stochastic wind power scenarios but while significantly reducing the computational burden associated with the calculation of the reserve deployment for each scenario. In [20] a robust optimization approach is developed to derive an optimal unit commitment decision for the reliability unit commitment runs by ISOs/RTOs with the objective of maximizing total social welfare under the joint worst-case wind power output and demand response scenario.

The rest of this paper is organized as follows. Section 2 presents the uncertainty modeling technique. Section 3 proposes the formulation of the problem and the solution methodology. One case study is studied in section 4. Section 5 concludes the discussion.

2. Uncertainty Modeling Technique

In order to taking into account wind power and demand forecasting uncertainty, we use an uncertainty modeling technique that is based on scenario generation for uncertain parameter. In this approach we use monte carlo simulation technique to generate a large number of scenarios subject to a normal distribution of forecasting errors that have engendered in the past predictions. Since the number of scenarios is very large, using all of those scenarios in solving progress increases the computational burden of our problem. Therefore, reducing the number of scenarios is one of the necessities. So, scenario generation and reduction methods are as follows:

2.1. Scenario Generation

For scenario generation, first we have to calculate the forecasting errors that have occurred in the past wind power and demand predictions and assume that they are subject to a normal or other statistical distribution with an expected value (μ) and a percentage of μ as its volatility (σ). Then, using monte carlo sampling technique, monte carlo paths will create by sampling from this distribution and juxtapose them. Now for constructing possible scenarios we must add the obtained samples to the predictions for next 24 hour, each scenario is assigned an occurrence probability.

2.2. Scenario Reduction

The scenario reduction technique is employed to decrease the number of obtained scenarios. Scenario reduction will remove scenarios that have low occurrence probability and conjunct those scenarios that are the same as each other, in one scenario [21], [22]. By reducing the number of scenarios consequently the computational burden and time will decrease remarkably.

3. Problem Formulation And Solution Methodology

3.1. Stochastic Programming

In many situations there is a need to make, an optimal, decision under conditions of uncertainty. There is a disagreement, however, with how to deal with such situations. Uncertainty can come in many different forms, and hence there are various ways how it can be modeled. In a mathematical approach one formulates an objective function f: $\mathrm{R}^n \rightarrow \mathrm{R}$ which should be minimized subject to specified constraints. That is, one formulates a mathematical programming problem:

$$\operatorname*{Min}_{x \in X} f(x), \tag{1}$$

Where the feasible set $X \subset \mathrm{R}^n$ is typically defined by a (finite or even infinite) number of constraints, say $X := \{x \in \mathrm{R}^n : g_i(x) \leq 0,\ i \in I\}$ (the notation ":=" means "equal by definition"). Inevitably the objective and constraint functions depend on parameters, which we denote by vector $\xi \in \mathrm{R}^d$. That is, $f(x, \xi)$ and $g_i(x, \xi)$, $i \in I$, can be viewed as functions of the decision vector $x \in \mathrm{R}^n$ and parameter vector $\xi \in \mathrm{R}^d$.

3.2. Problem Formulation

We formulate the UC problem in presence of wind power plants and hydro pump storage unit in (2) – (17) as a stochastic optimization problem. The objective function (2) consists of generator operating cost, start up and shutdown costs of thermal power plants and the cost of staring to generate or absorb power by pump storage unit. The constraints in our UC problem including system constraints, thermal power plant constraints, wind power plant constraints and pump storage unit constraints are as follows. System power balance constraint (3), system spinning reserve requirements (4), unit generation limits (5), unit minimum up time (6), unit minimum down time (7), unit ramping up limits (8), unit ramping down limits (9), unit initial state (10), hydro water inventory constraints (11), constraints (12) and (13) describe the upper and lower bounds of electricity absorbed and generated by the pumped-storage unit , constraints (14) and (15) give the initial and target water inventory level for the pumped-storage unit , water reservoir volume limit in pump storage unit constraint (16) and finally constraint (17) that ensures that the pumped-storage unit cannot absorb and generate electricity simultaneously within any specific time period .

$$\min \sum_{i=1}^{NG}\sum_{t=1}^{T}\left[F_{c,i}(P_{i,t})*I_{i,t}+SU_{i,t}+SD_{i,t}\right]+\sum_{h=1}^{NH}\sum_{t=1}^{T}\left[SGC_{h,t}+SPC_{h,t}\right] \tag{2}$$

$$\sum_{i=1}^{NG}P_{i,t}*I_{i,t}+\sum_{i=1}^{NW}P_{w,i,t}^{s}+\sum_{h=1}^{NH}\left[P_{h,i,t}^{out}-P_{h,i,t}^{in}\right]=D_{t}^{s} \tag{3}$$

$$\sum_{i=1}^{NG}R_{S,i,t}*I_{i,t}\geq R_{S,t} \tag{4}$$

$$P_{i,\min}I_{i,t}\leq P_{i,t}\leq P_{i,\max}*I_{i,t} \tag{5}$$

$$\left[X_{i,(t-1)}^{on}-T_{i}^{on}\right]*\left[I_{i,(t-1)}-I_{i,t}\right]\geq 0 \tag{6}$$

$$\left[X_{i,(t-1)}^{off}-T_{i}^{off}\right]*\left[I_{i,t}-I_{i,(t-1)}\right]\geq 0 \tag{7}$$

$$P_{i,t}-P_{i,(t-1)}\leq(2-I_{i,(t-1)}-I_{i,t})P_{i,\min}+(1+I_{i,(t-1)}-I_{i,t})RU_{i} \tag{8}$$

$$P_{i,(t-1)}-P_{i,t}\leq(2-I_{i,(t-1)}-I_{i,t})P_{i,\min}+(1+I_{i,(t-1)}+I_{i,t})RD_{i} \tag{9}$$

$$Y_{i,t}-S_{i,t}=I_{i,t}-I_{i,(t-1)} \tag{10}$$

$$Z_{t}=Z_{(t-1)}+A_{1}P_{h,t}^{in}-\frac{P_{h,t}^{out}}{A_{2}} \tag{11}$$

$$L_{h,t}^{in}\leq P_{h,t}^{in}\leq U_{h,t}^{in} \tag{12}$$

$$L_{h,t}^{out}\leq P_{h,t}^{out}\leq U_{h,t}^{out} \tag{13}$$

$$Z_{0}=Z_{begin} \tag{14}$$

$$Z_{T}=Z_{last} \tag{15}$$

$$V_{h,\min}\leq V_{h,t}\leq V_{h,\max} \tag{16}$$

$$IGH_{h,t}+IPH_{h,t}+IIH_{h,t}=1 \tag{17}$$

4. Case Study

4.1. Applying on a Sample System

As a case study we have considered a single bus system that includes 6 thermal units , 2 wind units and one hydro pump storage unit that have shown in fig.1 . The characteristics of thermal units and pump storage unit are presented in table.1 and table.2 respectively.

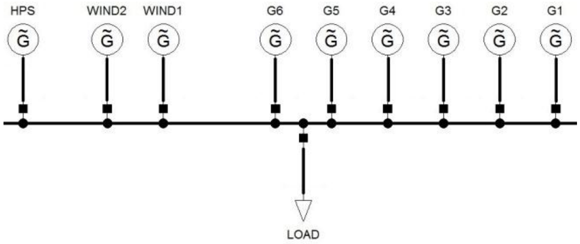

Fig.1. Studied system

Table.1
Generator data

Unit	Pmin (MW)	Pmax (MW)	Min ON (H)	Min Off (H)	Ramp Up (MW/H)	Ramp Down (MW/H)	IniT (H)
G1	100	580	10	10	250	250	10
G2	100	450	8	8	210	210	8
G3	100	380	6	6	175	175	6
G4	100	330	6	6	150	150	6
G5	100	300	5	5	150	150	5
G6	25	100	3	3	50	50	3

(a)

Unit	St Mbtu	Fuel Price ($/Mbtu)	af (Mbtu/MW^{2}h)	bf (Mbtu/MWh)	cf (Mbtu/h)
G1	300	1	0.0109	8.6	70
G2	250	1	0.01059	8.3391	64.16
G3	100	1	0.003	10.76	32.96
G4	440	1	0.01088	12.8875	6.78
G5	100	1	0.01088	12.8875	6.78
G6	50	1	0.0128	17.82	10.15

(b)

Each of the wind farms and required demand also has a predicted value and some scenarios for modelling uncertainty of the forecasted quantities. Figures 2, 3 and 4 show characteristics of wind unit 1, wind unit 2 and demand, respectively.

Table.2
Pump storage unit data

Unit	Pump Cycle Eff	Gen Cycle Eff	Max Gen Lim (MW)	Min Gen Lim (MW)	Max Abs Lim (MW)	Min Abs Lim (MW)	Min ON (H)	Min OFF (H)
1	0.8	0.8	40	5	40	5	1	1
	Uphill Reservoir				Downhill Reservoir			
Unit	Ini Vol (Hm^3)	Tgt Vol (Hm^3)	Up Lim Vol (Hm^3)	Low Lim Vol (Hm^3)	Ini Vol (Hm^3)	Up Lim Vol (Hm^3)	Low Lim Vol (Hm^3)	Gen And pump St Cost($)
1	180	60	250	50	380	600	200	75

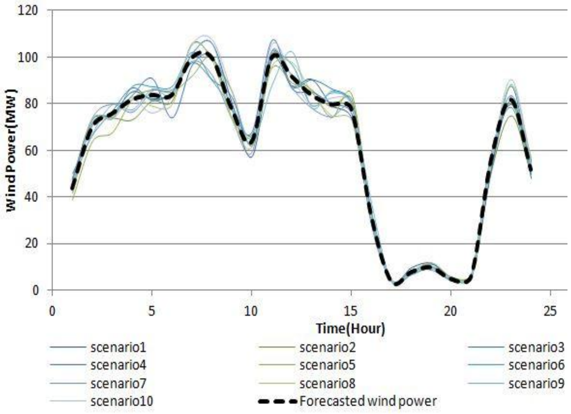

Fig.2. Forecasted power and scenarios for wind1

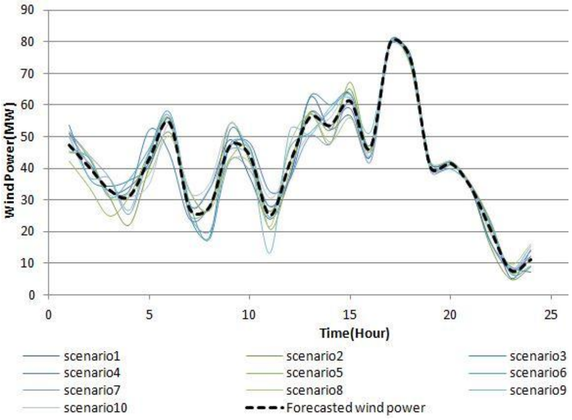

Fig.3. Forecasted power and scenarios for wind2

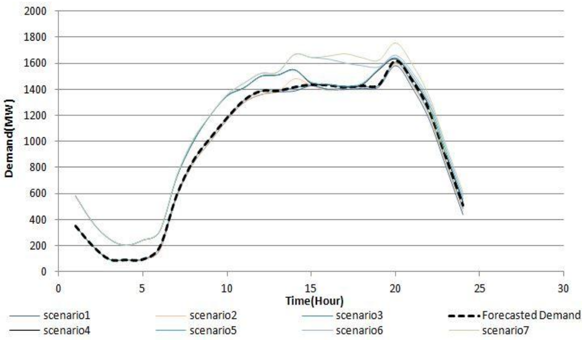

Fig.4. Forecasted demand and scenarios

By means of the introduced system we solve the UC and ED problem. In this paper we have used GAMS24.1.3 and its CPLEX solver to solve the Mixed Integer Program (MIP) that proposed in section 3.2.

After solving the problem we must choose the most optimum schedule of committing units in order to minimize the production cost. The output results of the program showed that the cost of the power production in the considered day is 353834.056$ and allocated power to each unit can be showed like table.3.

Table.3
Commitment and dispatch of thermal and pump storage units

Hour	G1 (MW)	G2 (MW)	G3 (MW)	G4 (MW)	G5 (MW)	G6 (MW)	H OUT (MW)	H IN (MW)
1	460.4	0	0	0	0	25	0	0
2	246.6	0	0	0	0	25	0	0
3	113.6	0	0	0	0	25	0	0
4	100	0	0	0	0	0	0	8.4
5	118.5	0	0	0	0	0	0	0
6	172.4	0	0	0	0	0	0	0
7	422.4	165.8	0	0	0	0	0	0
8	562.524	100	175	0	0	0	21.376	0
9	580	139	350	0	0	0	0	0
10	580	181.6	380	0	100	0	0	0
11	580	233.5	380	0	100	0	0	0
12	580	271.7	380	0	100	25	0	0
13	580	255.5	380	0	100	25	40	0
14	580	323.3	380	0	100	25	0	0
15	580	242.9	380	0	100	0	0	0
16	580	293.9	380	0	100	0	0	0
17	580	276.7	380	0	100	0	0	0
18	580	293	380	0	100	0	0	0
19	580	340.2	380	100	100	0	0	0
20	580	450	350	100	106.8	0	0	0
21	580	450	175	100	136.5	0	0	0
22	500	450	0	100	133.9	0	0	0
23	250	405.49	0	100	0	0	40	0
24	0	364.5	0	100	0	0	0	0

In order to ensure system reliability and security we have allocated spinning reserve for each hour. The spinning reserve is provided by thermal units by means of committing those thermal units in each hour that the sum of their maximum production capacity is greater than or equal by “1.15*Demand” in that hour.

In table.3 we can see that the pump storage unit , in the period of times that demand is low and wind production is high , treats like a load and absorbs power to pump water from downhill reservoir to uphill reservoir that . This work not only causes an increase in energy storage but also decreases the need to wind curtailment. Moreover this unit has used for peak shaving in times that a transition peak load has occurred and thus prevents from more start up in thermal units.

It is obvious that if the capacity of the pump storage unit be different from the value that we have used, its commitment will be different too. Figures 5 and 6 show the change in uphill and downhill water volume that have engendered because of the generating and absorbing power during the day. It is clear that the water volume had not transgressed from its limits both in downhill and uphill reservoirs and the volume in uphill reservoir have reached to the predefined value at the end of the day.

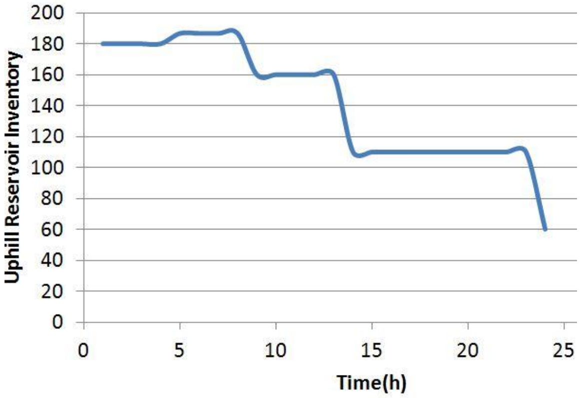

Fig.5. Uphill reserve inventory changes

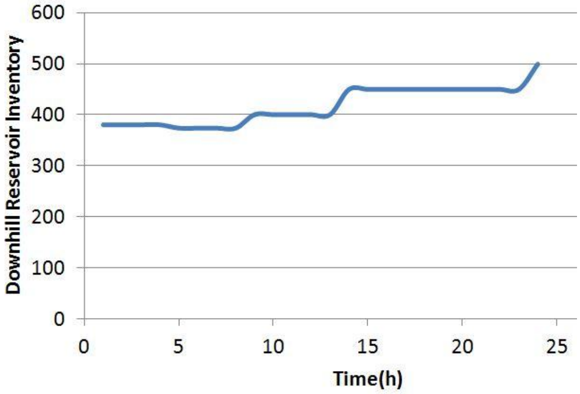

Fig.6. Downhill reserve inventory changes

4.2. Sensitivity Analysis

In order to evaluate the effect of some parameters on the problem we have done sensitivity analysis. By this goal we solved the problem without wind power plants and pump storage unit. Results show that this change increases the production cost to 394171.138$ that is equal to 11.4% increase and moreover the aggregate operating hour of units was increased too.

We have also examined the effect of changes in pump storage unit capacity and initial water volume in uphill reservoir on the production cost. Figures 7 and 8 show the change in production cost by varying the pump storage maximum capacity and initial water volume in the uphill reservoir, respectively.

It is sensible in fig.7 that the production cost at first decreases gradually as the maximum capacity of pump storage unit increases, but after a specific capacity the change in cost is more remarkable. It is why by increasing the capability of pump storage unit to take part in supplying the load and saving energy, the efficiency of it, is also increased.

Besides, Fig.8 shows that if the volume of the water that exists in the uphill reservoir at the beginning of the day be more than we considered, the production cost will also less than we obtained from the implemented volume as the initial water volume for the uphill reservoir of the hydro pump storage unit.

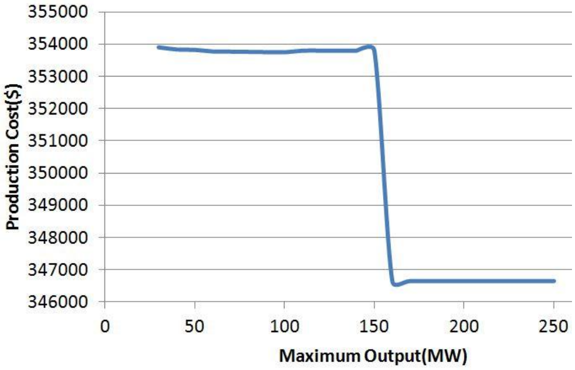

Fig.7. Cost change by varying maximum capacity of the pump storage unit

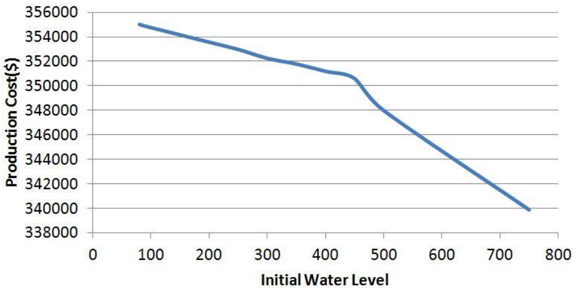

Fig.8. Cost change by varying initial water level in uphill reservoir

5. Conclusion

In this paper, we proposed an approach that includes applying optimization concepts and incorporating pumped-storage units to hedge wind power output uncertainty and peak shaving. We provided scenarios that can capture the wind power unpredicted changes and our proposed approach can provide an optimal solution that minimizes the total cost under the wind power fluctuations that can occur in the system, while ensuring the higher penetration of wind power. Meanwhile, this solution is feasible with a high probability under wind power output uncertainty. In addition, by incorporating pumped storage hydro units in the real time, our optimization model contains discrete decision variables in problems. Finally, our computational results verify the effectiveness of the presence of wind units and pump storage unit for the system and power production cost.

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