Improving Supply-Load Balance with Generator Outage by Battery Storage at High wind Penetration

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Abstract: Due to carbonization concern, generation resources of electrical energy needs great concern. Renewable energy source as wind which has low utilization cost used with integrated thermal power plants is gaining a lot of attention these days due to environmental concern. The high penetration of wind imbalances the system regarding with load variability and it needs flexile resources to compensate instantaneous costs by wind energy. Charging and discharging of the storage connected with wind units changes the unit-output. This paper presents the Security Constrained Unit Commitment (SCUC) integrated with 40% wind penetration. SCUC is handled by Mixed Integer Linear Programming (MILP) which is simulated in General Algebraic Modelling System (GAMS). Generator outage is a contingency introduced in the grid to compare the change in performance specification of a RTS 24 bus test system. In this paper, we discussed the simulation which has net output, the wind curtailment and load shedding. To compensate the overall cost, we have to work on load shedding which should be as minimum as possible.

Keywords: GAMS, MILP, RTS-24 bus test system, SCUC

NOMENCLATURE

Sets and indices:

$u \in U$	Dispatchable Generating Units
t	Index for Time period [hour]
b	Index for Bus
N	Index for Node
$w \in W$	Wind Generating Units
$s \in ST$	Storage Units

Parameters:

T	Number of time interval considered – 24
C_u^{op}	Operating Cost of unit u (\$/MWh)
$\overline{P}_u$ / $\underline{P}_u$	Maximum/minimum Power limits of unit u [Hour]
η_s^c / η_s^d	Charging/discharging efficiency of storage unit s
$SOC_s^{\max}$	Maximum limit of charging status of storage unit s
$SOC_s^{\min}$	Minimum limit of charging status of storage units s
RP_u^+ / RP_u^-	Ramp-up rate/Ramp-down rate limits of unit u [MW/h]
MU_u / MD_u	Minimum up/minimum down time of unit u [Hour]
S_u^+ / S_u^-	Start-up/Shut-down ramp limits of unit u [MW/h]
C_u^s / C_u^d	Start-up/Shut-down cost of unit u [\$]
$\gamma_{b,n}$	Admittance of line between bus b and node n
$P_{w,t}^A$	Available wind generation of unit w at time t [MW]
L_b^t	Total load at bus b at time t [MW]
$\lim_{b,n}$	Line limits between bus b and node n [MVA]
S_{base}	Base value of Apparent power
VLS	Value of load shed [\$/MWh]

Variables:

C_{gen}	Cost of generation [\$]
P_e^{ls}	Penalty of load shed [\$]
$P_{u,t}$	Power generation of unit u [MW]
H_u^{on}	On time of unit u [Hour]
H_u^{off}	Off time of unit u [Hour]
$P_{w,t}$	Wind generation of unit w [MW]
$P_{w,t}^c$	Wind curtailment of unit w [MW]
Ls_b^t	Load shedding at bus b at time t [MW]
$P_{s,t}^c$	Energy storage charging power units s at time t [MW]

$P_{s,t}^{d}$	Energy storage discharging power units s at time t [MW]
$SOC_{s,t}$	Charging status of storage units s at time t [MWh]
$l_{s,t}$	Energy storage charging binary variable for unit s (1-charging)
$m_{s,t}$	Energy storage discharging binary variable for unit s (1-discharging)
$v_{u,t}$	Unit commitment binary variable for unit u (1-on, 0-off)
$\alpha_{u,t}$	Start-up binary variable for unit u (1-start-up)
$\beta_{u,\mathrm{t}}$	Shut-down binary variable for unit u (1-shut-down)
$\delta_{b,t}$	Load angel of bus b at time t
$Fl_{b,n,t}$	Power flow from line between bus b and node n at time t

1. INTRODUCTION

Power system is a complex network due to interconnection of several transmission lines in a grid, it becomes more complex. To work under these complexity, it is a fundamental task to operate the system more reliably. The system is not economical if we run all thermal units at a time. Unit Commitment (UC) decides which time is suitable for which units to run and how long the particular unit runs. UC is an optimization technique to make a thermal system more economical. UC formulation is not applicable for nuclear and hydropower plants. The nuclear power plants are base load plants and if it is on then it will continuously run. With hydropower plants, there is no fuel means there is no optimization and it is quick to start. The thermal power plants take 2 to 8 hours to get started depending upon boiler condition. UC problem minimizes the fundamental costs which can be very high if all system of units run at a time.

In recent years, the renewable energy resources came into picture due to its environment friendly nature and also easy to available, wind energy is one of them. There are more uncertainties introduced at the time of integrating the wind energy in the thermal systems [1-2], these all uncertainties are removed by security constrained UC methodology for day ahead scheduling [3]. UC can be formulated by hierarchical strategy [4] in which the system is scheduled with high penetration of wind energy.

High wind penetration introduces more imbalance in terms of more load variability due to weather dependency. With the increment of wind penetration, the system faces more uncertainty [5]. With 35 percent of wind penetration [6], the system is having a good reliable state but the cost function does not improve with such a high penetration. To overcome this imbalance and to compensate wind energy, battery storage is used as flexible energy resources integrated with wind farms. These Energy Storage System (ESS) as Superconducting Magnetic Energy Storage (SMES) [7] increases the performance in the overall system in terms of reliability. The wind power and load variation require more Spinning Reserve under different scenarios [8]. The Particle Swarm Optimization (PSO) is used to improve overall solution quality and feasibility. To get an optimal solution of demand and wind farm with storage under various influential uncertainties [9], the hybrid system of the reduced cost was modeled by Non-Linear Mixed Integer UC.

There are two performance specifications used in this context and these are wind curtailment and load shedding. The wind curtailment is un-prediction of a day ahead of UC. Wind curtailment and load shed should be as minimum as possible to improve the savings. In [10], the rolling commitment is used to examine the characteristics and get good potential savings.

Due to un-prediction of wind energy, the wind thermal UC [11] can be a typical task to optimize the system and it is very challenging for operation. They used a linear model for prediction of the energy cost and up/down constraints.

The system with high wind penetration optimized by a stochastic approach for operation and planning is taken for cost minimization [12]. This technique is superior than a deterministic approach when we integrate the wind-thermal power plant. This integrated system is scheduled for 24-hour time horizon with generator outage. The methodology used in this paper Mixed Integer Linear Programming (MILP) and this integrated system is simulated in the General Algebraic Modelling System (GAMS).

2. PROBLEM FORMULATION

Thermal power generating units work under complex system constraints and it is very difficult to analyze all system constraints separately. The unit commitment optimize all possible statuses under constraints by a single technique.

There are three cases considered in this paper as: Case (1): UC-OPF without contingency andCase (2):- UC-OPF with contingency.

3. MATHEMATICAL FORMULATION

3.1 Objective Function

Minimizing overall operating cost of the system is objective function taken in this work. The operating costs consists of basically generating, start-up and shut-down cost. The objective function of this paper can be stated as:

$$Min\,C_{gen} = \sum_{u,t} P_{u,t} C_u^{op} + \sum_{u,t} C_u^{s} \alpha_{u,t} + \sum_{u,t} C_u^{d} \beta_{u,t} + \sum_{b,t} L_{b,t}^{s} VLS \quad (1)$$

3.1.1 Generating Cost

It is generally described by fuel cost function which gives the quadratic function with reference to production level which represents in \$/MWh.

3.1.2 Start-up Cost

This is the cost affecting by the thermal unit starting condition depends upon the status of thermal boiler temperature. Generator takes less time in hot boiler (the boiler which stops some time ago) and more time in cold boiler. Start-up cost may be different in both the cases.

3.1.3 Shut-down Cost

The generating unit gets off in some time for specific purposes. Shut-down cost may be different for all thermal units as start-up cost of generator unit.

3.1.4 Load Shedding

Sometimes generating units generate less energy than demand at load end. To run the entire system more reliable, there has to shut down some distribution areas which is decided by UC. We focus on running the costlier units due to high start-up and shut-down costs.

3.2 Unit Constraints

The generating system has these following constraints. We considered a 12 units system in this paper which have some fixed values of every constraint which are given in the Table 1 below.

Table1: Unit Constraints Data

Unit	O C (\$/MWh)	Min Cap (MW)	Max Cap (MW)	R U (MW/h)	R D (MW/h)	M Up Time (h)	M Down Time (h)
U1	5.47	100	400	6.7	6.7	1	1
U2	5.47	100	400	6.7	6.7	1	1
U3	13.32	30.4	152	2	2	8	4
U4	13.32	30.4	152	2	2	8	4
U5	10.52	54.25	155	3	3	8	8
U6	10.52	54.25	155	3	3	8	8
U7	10.52	108.5	310	3	3	8	8
U8	10.89	140	350	4	4	8	8
U9	20.70	75	350	7	7	8	8
U10	20.93	206.8	591	3	3	12	10
U11	26.11	12	60	1	1	4	2
U12	0.00	300	300	5	5	0	0

3.2.1 Up ramp and down ramp limits

The ramp rate is the rate of change of output over a unit time. The up and down ramp limits of thermal unit are given below in (2-3).

$$P_{u,t} - P_{u,t-1} \le RU_u^{+} v_{u,t-1} + S_u^{+} \alpha_{u,t} \quad \forall u,t \quad (2)$$

$$P_{u,t-1} - P_{u,t} \le RP_u^{-} v_{u,t} + S_u^{-} \beta_{u,t} \quad \forall u,t \quad (3)$$

3.2.2 Unit Status Equation

Unit status is defined as ON/OFF status coding as binary code 1 or 0. The binary code 1 indicated the ON status and 0 indicated the OFF status which can be seen in equation 4. Equation 5 indicates the start-up and shut-down unit status are working simultaneously.

$$\alpha_{u,t} - \beta_{u,t} = v_{u,t} - v_{u,t-1} \quad \forall u,t \quad (4)$$

$$\begin{aligned} &\alpha_{u,t} \in \{0,1\} \\ &\beta_{u,t} \in \{0,1\} \\ &\alpha_{u,t} + \beta_{u,t} \le 1 \quad \forall u,t \end{aligned} \quad (5)$$

3.2.3Generation Power Limit

Any generating units generate power within its boundary. These limits are given in equation 6 stated as:

$$\underline{P}_u v_{u,t} \le P_{u,t} \le \overline{P}_u v_{u,t} \quad \forall u,t \quad (6)$$

3.2.4 Unit minimum up and down time

Any thermal unit has some time to operate, that operating time is scheduled by unit commitment. The minimum up/down time of any generating unit is given by:

Minimum up time

$$\sum_{t=1}^{\Upsilon_u} (1 - v_{u,t}) = 0 \quad (7)$$

$$\sum_{t=k}^{k+MU_u-1} v_{u,t} \ge MU_u \alpha_{u,t} \quad (8)$$

$$\forall k = \Upsilon_u + 1 \ldots T - MU_u + 1$$

$$\sum_{t=k}^{T} (v_{u,t} - \alpha_{u,t}) \ge 0 \quad (9)$$

$$\forall k = T - MU_u + 2 \ldots H$$

Where, $\Upsilon_u = Min[T, (MU_u - H_u^{on}) v_u^0]$

Minimum down time

$$\sum_{t=1}^{\Psi_u} v_{u,t} = 0 \quad (10)$$

$$\sum_{t=k}^{k+MD_u-1} (1 - v_{u,t}) \ge MD_u \beta_{u,t} \quad (11)$$

$$\forall k = \Psi_u + 1 \ldots T - MD_u + 1$$

$$\sum_{t=k}^{T} (1 - v_{u,t} - \beta_{u,t}) \ge 0 \quad (12)$$

$$\forall k = T - MD_u + 2 \ldots H$$

Where, $\Psi_u = Min[T, (MD_u - H_u^{off})(1 - v_u^0)]$

3.2.5 Power flow Equation

Power transmitted from transmitting end to receiving end is known as power flow which depends on power angle defined by delta. The p.u. value of the power flow should be limited by minimum to maximum value of the power at the bus.

$$Fl_{b,n,t} = \gamma_{b,n}(\delta_{b,t} - \delta_{n,t}) \ldots \; \forall b,n,t \quad (13)$$

$$-\lim_{b,n} / S_{base} \le Fl_{b,n,t} \le \lim_{b,n} / S_{base} \ldots \forall b,n,t \tag{14}$$

3.3 Wind Generation Constraints

Wind generating station generates wind energy and mixed up in the thermal plants in coordination to balance the overall power, the total amount of both power should be alwaysless than available power.

$$P_{w,t} + P^c_{w,t} \le P^A_{w,t} \qquad \forall w,t \tag{15}$$

$$0 \le P_{w,t} \le P^A_{w,t} \qquad \forall w,t \tag{16}$$

$$0 \le P^c_{w,t} \le P^A_{w,t} \qquad \forall w,t \tag{17}$$

3.4 Storage Constraints

To overcome the effect of load shedding, we introduced battery storage. It also helps in storing the extra energy which is at the time of OFF status of wind and thermal units.

$$SOC_{s,t} = SOC_{s,t-1} + (P^c_{s,t}\eta^c_s - P^d_{s,t} / \eta^d_s)\Delta t \ldots \forall s,t \tag{18}$$

$$\underline{SOC}_s \le SOC_{s,t} \le \overline{SOC}_s \ldots \forall s,t \tag{19}$$

$$\underline{P}^c_s l_{s,t} \le P^c_s(t) \le \overline{P}^c_s l_{s,t} \qquad \forall s,t \tag{20}$$

$$\underline{P}^d_s m_{s,t} \le P^d_s(t) \le \overline{P}^d_s m_{s,t} \qquad \forall s,t \tag{21}$$

$$l_{s,t} + m_{s,t} \le 1 \qquad \forall s,t \tag{22}$$

3.5 System Constraints

Power balance Constraints

The incoming power at any bus is always equal to outgoing power at that bus. The some part of electrical power flows through transmission line and some dissipated in the load. In case of penetration of wind the overall power at bus is stated as:

$$\sum_{u\in b} P_{u,t} + \sum_{w\in b} P_{w,t} + L^s_{b,t} + \sum_{s\in b} P^d_{s,t} - \sum_{s\in b} P^c_{s,t} - L_{b,t} = \sum_{n\in b} Fl_{b,n,t} \qquad \forall b,t \tag{23}$$

4. UC TEST SYSTEM

UC is an optimization technique to optimize thermal units of IEEE test system. The system is used in this paper is RTS 24 bus system in which there are 24 bus and 32 transmission lines interconnected in a manner to make a complete grid. Total capacity of all conventional units is 3375 MW.

The generation plants can be categorized in 1st and 2nd as nuclear, 3rd, 4th, 5th, 6th and 7th as Coal/Stream, 8th as Coal/3 Stream, 9th, 10th and 11th as Oil/Stream and 12th as Hydropower plant.The topology of the overall power grid consists of 3 transformers and 17 loads connected to all buses except bus number 11, 12, 17, 21, 22, 23 and 24.There are 32 number of transmission lines to make a complete grid. Which have reactance and the line limit as given in Table 2.

The average of more than 5000 randomly chosen Monte Carlo Simulated data which is taken by Weibull distribution is used in this paper. High wind penetration of 2000 MW having 40% of total generation is plotted hourly basis in Figure 1, this is taken by 30 years of historical data [13].

Table 2: Transmission Line Data

From	To	Y (p.u.)	Power (MVA)	From	To	Y(p.u.)	Power (MVA)
1	2	66.67	175	11	13	20.83	500
1	3	4.444	175	11	14	23.25	500
1	5	10.99	350	12	13	20.41	500
2	4	7.353	175	12	23	10.20	500
2	6	4.878	175	13	23	11.36	500
3	9	7.874	175	14	16	16.95	500
3	24	11.90	400	15	16	58.83	500
4	9	9.010	175	15	21	40	1000
5	10	10.64	350	15	24	18.18	500
6	10	15.62	175	16	17	38.46	500
7	8	15.38	350	13	19	43.48	500
8	9	5.682	175	17	18	71.43	500
9	11	11.90	400	18	21	76.92	1000
9	12	11.90	400	19	20	50	1000
10	11	11.90	400	20	23	90.91	1000
10	12	11.90	400	21	22	14.49	500

The load demand can be seen in the Figure 1.

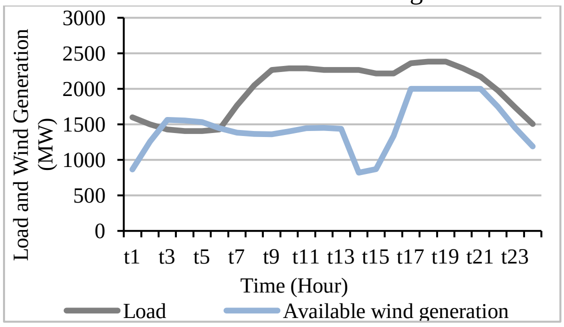

Figure 1: Load Demand and Wind Generation Profile for Complete Day

For better analysis, this paper consists of two cases given below:

Case 1: UC-OPF without contingency

1. *Case A: Scheduling units without wind penetration*

This case is an introductory case in which the RTS 24 bus system is scheduled for 24 hour without wind energy. Each unit has its own characteristics. The variation of load profile can be seen in Figure 2.

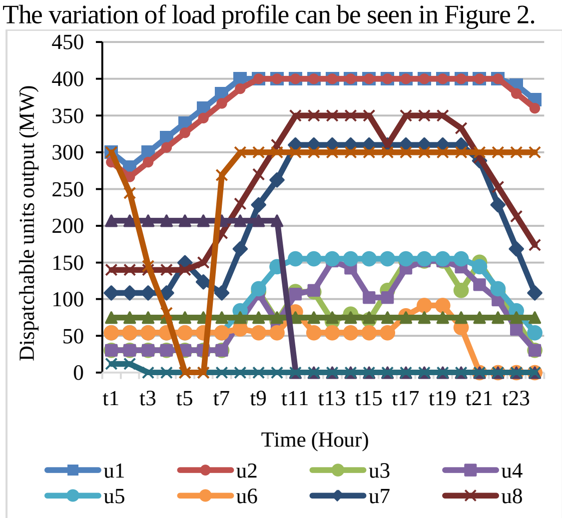

Figure 2: Dispatchable Units Output without Contingency

2. *Case B: Scheduling units with wind penetration*

In this case, 40% wind penetration is given in RTS 24 bus –system at 10th, 13th, 14th, 15th and 23rd number of bus. The load variation profile can be seen in the Figure 3. In which we can see the load shedding at particular time. Whenever the net load is more than unit out, the load shedding occurs. This load shedding affects the system operational costs. The total wind curtailment and load shedding are 6934 MW and 105 MW respectively.

3. *Case C: Scheduling units with battery storage*

In order to reduce load shedding, we use battery as flexible resources in the wind farm. The charging and discharging of the battery decided by the difference between net load and unit output. The unit output is more than net load (light load or peak load condition), then the extra load is responsible to charge the battery. Charging is shows negatively in the Figure 4. In case of off-peak hours, the battery discharges. Discharging shows positively in the Figure 4. The battery in the wind farm also reduces the wind curtailment and load shedding. In this case there is no load shedding but the value of wind curtailment is 6512 MW. It compensates the system operational costs.

Figure 3: Load Shed at Wind Penetration without Contingency

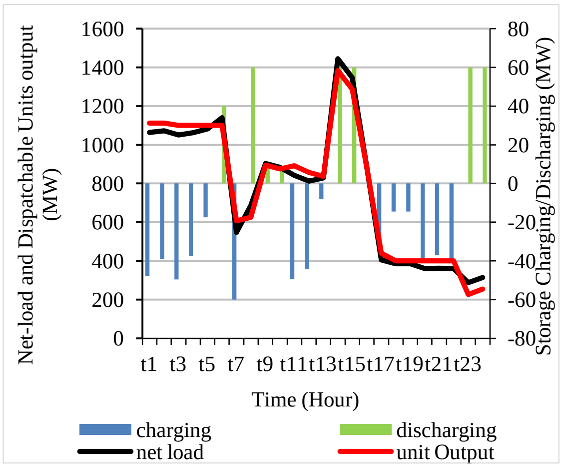

Figure 4: Storage Charging/Discharging without Contingency

Case 2: Introduction with Generator outage

1. Case A: Scheduling units without wind penetration

There is an abnormal condition occurs in the system which can be seen as generator outage contingency. This affects the load profile of each unit and the dispatchable units output for complete day can be seen in Figure 5.

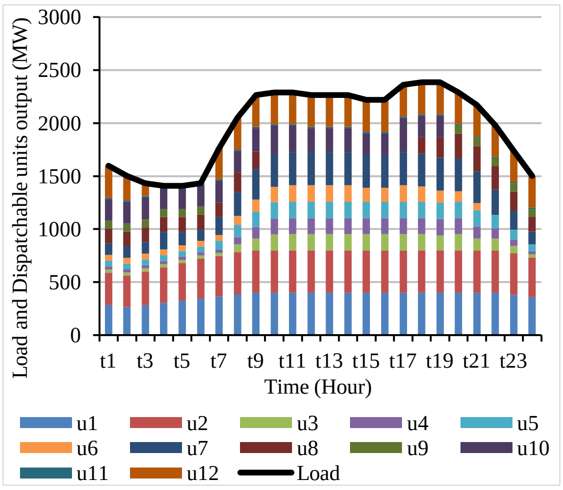

Figure 5: Dispatchable Units Outputwith Generator Outage Contingency

2. Case B: Scheduling units with wind penetration

In this case, each unit is scheduled after generator outage. At peak load time, the net load is more than unit output. This gap between net load and unit output introduces the load shed. In thiscontingency wind curtailment and load shedding are 7186 MW and 167 MW respectively can be seen in the Figure 6. These are responsible in increment of the operational cost.

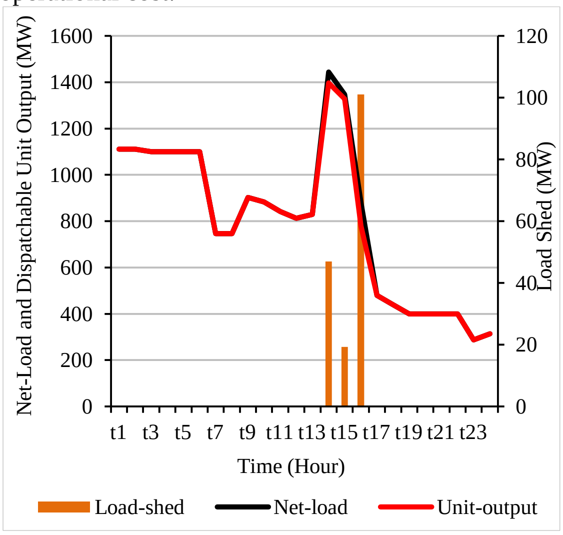

Figure 6: Load Shed at Wind Penetration with Generator Outage Contingency

3. Case C: Scheduling units with battery storage

In this case, the system has generator outage contingency. Due to this unit outage, the system faces wind curtailments and load shedding. This battery storage overcomes the value of wind curtailment and load shedding which are now 6733 MW and 0 MW respectively. In case of peak load, the battery gets charges and discharges in case of off-peak load time. The storage charging and discharging can be seen in the Figure 7.

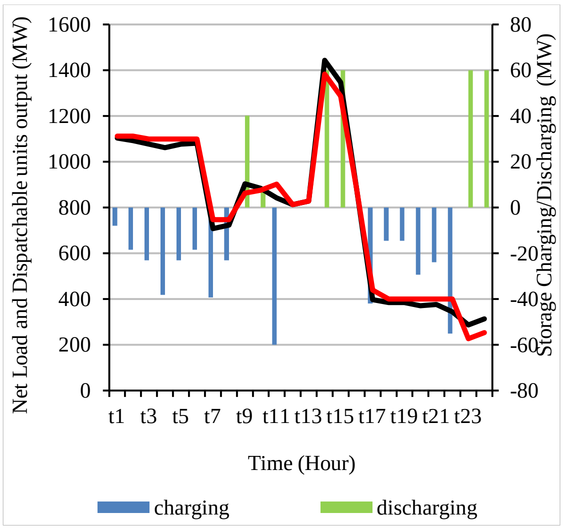

Figure 7: Storage Charging/Discharging with Generator Outage Contingency

4 CONCLUSION

The wind energy is one of the most clean renewable energy which is widely used in the world to integrate with the conventional power plants. To reduce production cost in terms of penalty, introduction of battery in the wind farm as flexible resource is very necessary. This storage makes the entire system more reliable. The overall cost minimizes in the case of less load shedding analyzed with and without contingency. The overall performance regarding to reduction in wind curtailment and load shedding can be seen in the table given below. Result shows that battery storage with wind plants increases reliability in terms to make system more economic.

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