Optimized Generation Scheduling of Thermal Generators Integrated to Wind Energy System with Storage

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Abstract- The rising energy demand and climate change issues have warranted the inclusion of renewable energy resources with existing conventional fuel based generation system. The intermittent renewable generation require adequate battery support in order to minimize load deficit issues in electrical grid. Hence, an attempt has been made in this paper to formulate a short term deterministic Unit Commitment problem in renewable integrated environment with battery storage. Ten thermal generators are scheduled with a 500 MW wind energy generation system supported by 200 MWh battery with backup of four hours. A three stage solution methodology is evolved involving hybrid Particle Swarm Optimization (PSO) technique to provide techno-economic solution to this complex optimization problem. The charge/ discharge scheduling of battery energy storage integrated to wind generation system is taken up as a co-optimization problem. The generation of battery energy storage integrated wind energy system is so scheduled that it relieves the costlier thermal generating units in the most economic manner.

Keywords Unit Commitment Problem (UCP); priority list method (PLM); particle swarm optimization technique with time varying acceleration coefficients (PS0_TVAC); battery energy storage (BES); wind energy system (WES).

1. Introduction

Sporadic and rapidly draining conventional fuels and the climate change concerns have necessitated the inclusion of abundantly and freely available Renewable Energy Resources (RERs) into main stream power generation systems [1,2]. The Wind Energy Systems (WES) is preferred over other RERs as it is more sustainable, cleaner and cheaper [3,4]. The main problem associated with WES is its intermittency. The wind speed alters significantly over 24 hours leading to a large variation in its output power. This intermittent nature may cause stability issues in the Grid [5, 6]. This problem can be circumvented to some extent by implementing in conjunction the Energy Storage Systems (ESS) [7-10]. Among the variety of existent ESS technologies like fly wheel storage, super capacitor storage, hydrogen storage, battery storage etc., battery storage has demonstrated its dominance based on techno-economic benefits in high storage applications [11-13]. The Battery Energy Storage (BES) can operate upon a wide range of power starting from tens of MW to hundreds of MW over several hours [14]. Application of BES has found a significant role in power systems because it not only provides reliability to the Grid but also proves to be a cost effective substitute for meeting the prevalent demand [15]. In this era of advancements in the relevant technology, the use of BES is likely to prove itself to be the most viable storage system in coming future [16].

The Unit Commitment Problem (UCP) is a highly intricate optimization problem governed by multiple constraints [17-19]. Combinations of the variety of available generation resources need to be designated optimally in order to achieve the overall optimized cost of generation while meeting the prevailing demand.

The problem becomes more complex when WES and BES are imbibed in UCP model. The charge-discharge schedule of battery in a Grid connected system requires greater focus as the cost of thermal generation is required to be minimized for 24 hours. This is in contrast to the situation in Micro Grid systems where the objective is just to satisfy the demand throughout the day.

In a Micro Grid system, the charge-discharge schedule of BES is decided in a simpler way. Maintaining the battery constraints, the battery is charged when the generation is greater than the demand and is discharged when the situation is contrary [17, 18]. This method may not prove worthy when WES works in conjunction with the thermal generators because thermal generators are capable of meeting the demand alone, so the condition of demand exceeding the generation never arises. It is only the matter of economic concern that by taking BES integrated WES generation scheduling as a co-optimization problem, the costlier MW generation of thermal units can be replaced by BES integrated WES resulting in overall reduced cost of generation.

2. Problem Formulation

The objective of the study is to obtain most economical operating schedule of thermal generation when nearly freely available BES integrated WES is blended with the existing thermal generation. The operating cost of BES integrated WES is neglected [20-22]. Thus the objective function of the problem is to minimize the overall cost of thermal generation for 24 hours in this new environment [23-25].

$$Cost_{NH} = \sum_{h=1}^{H} \sum_{i=1}^{N} [FC_i(P_{ih}) + SC_i(1 - U_{i(h-1)})]U_{ih} \tag{1}$$

U_{ih} is the ON/OFF status of the i^{th} unit at h^{th} hour.

$FC_i\ (P_{ih})$ is the fuel cost of i^{th} unit with power output (P_{ih}) at the h^{th} hour. FC is fuel cost function which is a quadratic polynomial with coefficients a_i, b_i and c_i. It is represented by Equation (2).

$$FC_i\left(P_{ih}\right) = a_i + b_i P_{ih} + c_i P^2_{ih} \tag{2}$$

The start-up cost *(SC_i)* of i^{th} unit is considered on the basis of minimum down time of unit *(MD_i)*, given by equation (3).

$$SC_i = \begin{cases} HSc_i: & X_i^{off} \le (MD_i + Cs_i)hrs \\ CSc_i: & X_i^{off} > (MD_i + Cs_i)hrs \end{cases} \tag{3}$$

H_{sc} is the hot start-up cost, C_{sc} is cold start-up cost. C_{si} is cold start-up hours, X_i^{off} is the duration in which i^{th} unit is continuously OFF.

The constraints of UCP considered here are as follows [25].

2.1 Thermal Generation Constraints

(i) Power Balance Constraint

$$\sum_{i=1}^{N} P_{ih} U_{ih} = LD_h \tag{4}$$

P_{ih} is the generation in MW of i^{th} unit in h^{th} hour and LD_h is the load demand at h^{th} hour.

(ii) Spinning Reserve Constraint

$$\sum_{i=1}^{N} P_{i(\max)} U_{ih} \ge LD_h + SR_h \tag{5}$$

$Pi_{\ (max)}$ is the maximum generation in MW of i^{th} unit and SR_h is the spinning reserve at h^{th} hour. In this paper for ten thermal generating units the spinning reserve is taken as 5% of total load.

(iii) Generation Limit Constraint

$$P_{i(\min)} \le P_{ih} \le P_{i(\max)} \tag{6}$$

(iv) Minimum up time constraints

$$X_i^{on}(t) \ge MU_i \tag{7}$$

X_i^{on} is the duration in which i^{th} unit is continuously ON.

(v) Minimum down time constraint

$$X_i^{off}(t) \ge MD_i \tag{8}$$

(vi) Initial Status

It is the initial down time status that is required to be considered in the first hour of scheduling. The data regarding thermal generating units and load profile is given in Appendix 1 and Appendix 2 respectively.

2.2 BES integrated WES generation model

In WES model the hourly wind power can be calculated from equation (9) [25].

$$Pw_h = \begin{cases} 0: & Vw_h < V_1; Vw_h > V_3 \\ \xi(Vw_h) & V_1 \le Vw_h \le V_2 \\ Pw_n & V_2 \le Vw_h \le V_3 \end{cases} \tag{9}$$

Where V_3, V_2 and V_1 are the cut out, rated and cut in speeds respectively, for wind turbine. Vw_h is wind speed according to hourly forecast [25].The function $\xi(v_{w_h})$ determines wind to energy conversion. Pw_n is the rated power of wind generation plant . $\xi(v_{w_h})$ can be expressed by equations (10-12) [25].

$$\xi(v_{w_h}) = k_o + k_1 v_{w_h}^2 \quad (10)$$

$$k_o = \frac{P_{wn} * v_1^2}{v_1^2 - v_2^2} \quad (11)$$

$$k_1 = \frac{P_{wn}}{v_2^2 - v_1^2} \quad (12)$$

Where, k_o and k_1 are constants.

The hourly wind speed data is given in Appendix 3.

The total available wind power output from the above equations is utilized in optimally the charging the battery while the remaining available wind power is directly dispatched to the Grid it is represented by equation (13). To avoid additional computational burden the efficiency of converters for ac/dc conversions are taken as 100% [26].

$$Pw_h = Pw_h^D + Pw_h^{BC} \quad (13)$$

Where, Pw_h^D and Pw_h^{BC} are the hourly power output of the available wind power for direct dispatch and optimally charging the battery.

The Lead-acid battery model is considered as [27]. The charging and discharging of battery can be explained with the help equations (14-21) [27]. The State of Charge (SOC) of battery during charging process is given as equation (14)

$$SOC_{h+1} = SOC_h * [1 - \sigma_h] + \frac{I_h^b * \Delta h * \eta_h}{C_b} \quad (14)$$

Where, σ_h is the hourly self-discharge rate taken as 0.02%, C_b is battery capacity in Ah, Δh is taken as 1 and η_h is charge efficiency factor given as equation (15).

$$\eta_h = 1 - \exp\left[\frac{y * SOC_h - 1}{\left(\frac{I_h^b}{I_0} + z\right)}\right] \quad (15)$$

Where, y, z and I_0 are the parameters depending upon working conditions of battery.

The battery charging current I_h^b, is given as equation (16).

$$I_h^b = \frac{Pw_h^{BC}}{V_h^b} * \eta_h^{conv} \quad (16)$$

η_h^{conv} is converter efficiency.

The battery discharge process is computed as equations (17-18).

$$SOC_{h+1} = SOC_h * [1 - \sigma_h] - \left(\frac{I_h^b * \Delta h}{C_b}\right) \quad (17)$$

Where,

$$I_h^b = -\left[\frac{P_h^{BD}}{V} * \eta_h^{conv}\right] \quad (18)$$

Where, P_h^{BD} is battery power discharged to the Grid.

Meanwhile, the charged quantity of the battery is subjected to following constraints [27].

$$SOC_{\min} \le SOC_h \le SOC_{\max} \quad (19)$$

And,

$$I_h^{b\max} = \max\left\{0, \min\left[I^{\max}, C_b * k\left((\mathrm{A}) + (\mathrm{B}) * (1-k)\right)/\Delta h\right]\right\} \quad (20)$$

Where,

$$\mathrm{A} = SOC_{\max} - SOC_h;\ \mathrm{B} = SOC_h - SOC_{\min}$$

And,

$k = 1$ for charging and $k = 0$ for discharging.

$$SOC_{\max} = 1;\ SOC_{\min} = 1 - DOD$$

DOD is Depth of Discharge, taken as 30% [27].

The battery terminal voltage (V_h^b) is given as [27]

$$V_h^b = V_h^{oc.b} + I_h^b * R_h^b \quad (21)$$

Where, $V_h^{oc.b}$ is open circuit voltage of battery and R_h^b is battery internal resistance.

The power balance constraint given in equation (4) can be modified to include BES integrated WES and the same is expressed by equation (22).

$$\sum_{h=1}^{H}\left[\sum_{i=1}^{N} P_{ih} U_{ih} + Pw_h + P_h^{BD}\right] = LD_h \quad (22)$$

3. Solution Methodology

A three stage solution methodology is proposed for solving Thermal Unit Commitment problem in BES integrated WES environment. The solution methodology can be explained from Fig.1.

3.1 Stage One

In first stage according to the hourly load demand [28] and thermal generators profile, priority listing of units is done by PLM. The initial priority vector is obtained as equation (23) [28].

$$priorityvector = \frac{P_{(\max),vec}}{\max.\left[P_{(\max),vec}\right]} + \frac{MD_{vec}}{\max.\left[MD_{vec}\right]} \quad (23)$$

This initial priority vector is updated with the help of the pseudo code as [28].

3.2 Stage Two

Among the ON thermal generating units load is economically allotted using PSO_TVAC. The PSO_TVAC can be expressed as equations (24-28) [29-30]. The velocity update of particle is given as equation (24).

$$v_{id}^{(k+1)} = [\omega * v_{id}^{k} + c_1 * Rand_1() * (A*) + c_2 * Rand_2() * (B*)] \quad (24)$$

Where,

$$A* = P_{bestid} - x_{id}^{k} \; ; \; B* = G_{best\ gd} - x_{id}^{k}$$

The position update of the particle is given as equation (25)

$$x_{id}^{(k+1)} = x_{id}^{k} + v_{id}^{k+1} \quad (25)$$

The inertia weight (w) of the particle varies as equation (26).

$$w = w_{max} - (\frac{w_{max} - w_{min}}{iter_{max}}) * iter \quad (26)$$

To deal with non-linearity of the problem acceleration coefficients *(c_1, c_2)* are taken as equations (27-28) [29-30].

$$c_1 = (c_{1f} - c_{1i}) * \frac{iter.}{iter_{max}} * c_{1i} \quad (27)$$

$$c_2 = (c_{2f} - c_{2i}) * \frac{iter.}{iter_{max}} * c_{2i} \quad (28)$$

The velocity limits and PSO_TVAC parameters are taken as [29-30].

Table 1- PSO_TVAC Parameters

Parameter	**Value**
Population Size	50
W_{max}	0.9
W_{min}	0.4
C_{1f}, C_{1i}, C_{2f}, C_{2i},	0.5, 2.5, 2.5, 0.5

3.3 Stage Three

In the third stage, the hourly dispatch schedule of thermal generators is saved in a look-up table. In accordance to the hourly thermal generation the generation costs of individual thermal generators is calculated and saved in descending order of priority. This information is conveyed to the BES integrated WES model where all the details regarding availability of hourly wind generation and battery are saved. In this block the battery charging and discharging is optimally decided based on availability of wind power and cost of thermal generation. The hourly generation cost of individual thermal generators serves as the basis for this co-optimization problem.

The hourly costlier MW entry from thermal generation gets replaced by respective hourly generation from wind as direct dispatch. If there is no costly thermal generation left out in that hour and still there is availability of wind power then the remaining wind power is used to charge the battery. Once battery is above its minimum SOC level then it gets discharged at the hours, of costlier generation from thermal power.

This process is continued for all 24 hours. This wind-battery power schedule is sent to update schedule block where the hourly optimized generation from BES integrated WES is subtracted from original dispatch schedule saved in look-up table. The updated generation schedule is dispatched to serve the hourly load demand.

This approach provides an optimal scheduling of BES integrated WES with thermal generation in order to optimize the overall cost of generation.

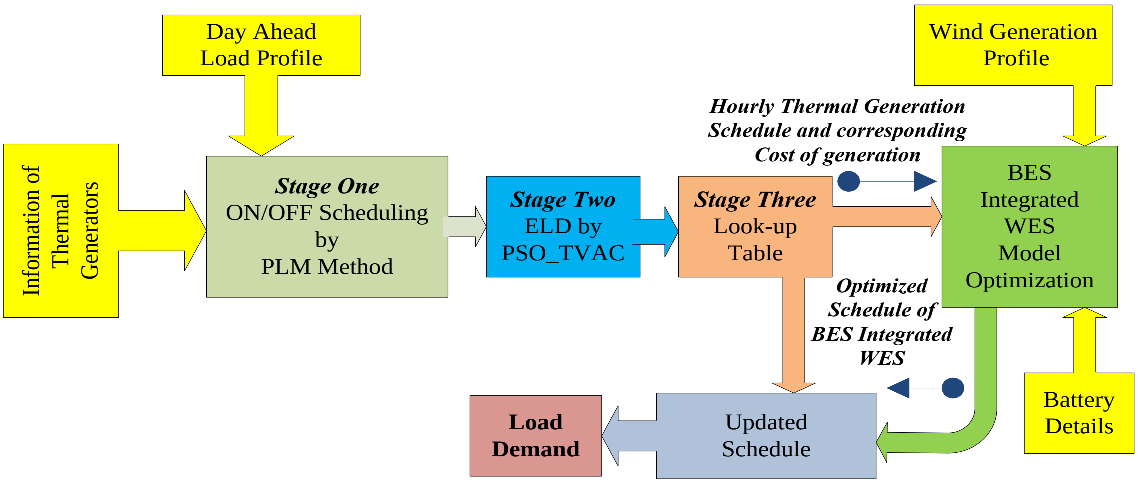

Fig.1 Block Diagram representation of solution methodology

4. Simulation and Results

The solution to the problem for the two cases, first when the load is entirely satisfied by thermal generation and second, when the load is satisfied by thermal generation in conjunction with BES integrated WES generation is given in Table 2 and Table 3 respectively.

The *green* color shows the ON status of thermal units obtained by stage one and the MW entries show the dispatch obtained by stage two.

Table 2. Unit Commitment for Thermal Generation

Hrs	**Thermal Generators (TGs)**												
	TG1	**TG2**	**TG3**	**TG4**	**TG5**	**TG6**	**TG7**	**TG8**	**TG9**	**TG10**	**Tot. Gen. (MW)**	**FC ($)**	**SC ($)**
H1		245									700	13683	0
H2		295			0						750	14554	0
H3		395		0							850	16302	0
H4		455	0		40						950	18598	900
H5		390			25	0	0				1000	20020	560
H6		455			60			0	0		1100	21860	0
H7		410			25						1150	23262	1100
H8					30						1200	24150	0
H9					110	20					1300	26589	340
H10						43					1400	29366	520
H11			130			80		13			1450	31220	60
H12		455			162	80	25	53	10		1500	33205	60
H13	455					43				0	1400	29366	0
H14				130	110	20					1300	26589	0
H15					140						1200	24318	0
H16		440			25			0	0		1050	20896	0
H17		390	0			0					1000	20020	0
H18					60						1100	21860	0
H19					140	20	0				1200	24318	170
H20		455			162	48		10	10		1400	30164	670
H21					110	20					1300	26589	0
H22		385	130								1100	21879	0
H23		315			0	0		0	0		900	17795	0
H24		215		0							800	16053	0

Table 3. Unit Commitment of Thermal Generation with BES integrated WES

<table>
<tr><th rowspan="2">Hrs.</th><th colspan="10">Thermal Generators (TGs)</th><th rowspan="2">BES Integrated WES Generation (MWs)</th><th rowspan="2">Tot. Gen. (MWs)</th><th rowspan="2">FC ($)</th><th rowspan="2">SC ($)</th></tr>
<tr><th>TG1</th><th>TG2</th><th>TG3</th><th>TG4</th><th>TG5</th><th>TG6</th><th>TG7</th><th>TG8</th><th>TG9</th><th>TG10</th></tr>
<tr><td>H1</td><td rowspan="22">455</td><td>245</td><td rowspan="6">0</td><td rowspan="4">0</td><td rowspan="3">0</td><td rowspan="8">0</td><td rowspan="9">0</td><td rowspan="10">0</td><td rowspan="11">0</td><td rowspan="24">0</td><td>0</td><td>700</td><td>13683</td><td>0</td></tr>
<tr><td>H2</td><td>295</td><td>0</td><td>750</td><td>14554</td><td>0</td></tr>
<tr><td>H3</td><td>369</td><td>26</td><td>850</td><td>15847</td><td>0</td></tr>
<tr><td>H4</td><td>455</td><td>40</td><td>0</td><td>950</td><td>18598</td><td>900</td></tr>
<tr><td>H5</td><td>390</td><td rowspan="11">130</td><td>25</td><td>0</td><td>1000</td><td>20020</td><td>560</td></tr>
<tr><td>H6</td><td>455</td><td>60</td><td>0</td><td>1100</td><td>21860</td><td>0</td></tr>
<tr><td>H7</td><td>410</td><td rowspan="8">130</td><td>25</td><td>0</td><td>1150</td><td>23262</td><td>1100</td></tr>
<tr><td>H8</td><td rowspan="6">455</td><td>30</td><td>0</td><td>1200</td><td>24150</td><td>0</td></tr>
<tr><td>H9</td><td>90</td><td>20</td><td>20</td><td>1300</td><td>26179</td><td>340</td></tr>
<tr><td>H10</td><td rowspan="4">162</td><td>26</td><td rowspan="4">25</td><td>17</td><td>1400</td><td>28979</td><td>520</td></tr>
<tr><td>H11</td><td rowspan="2">80</td><td>13</td><td>0</td><td>1450</td><td>31220</td><td>60</td></tr>
<tr><td>H12</td><td>53</td><td>10</td><td>0</td><td>1500</td><td>33205</td><td>60</td></tr>
<tr><td>H13</td><td>43</td><td rowspan="7">0</td><td rowspan="7">0</td><td>0</td><td>1400</td><td>29366</td><td>0</td></tr>
<tr><td>H14</td><td>312</td><td rowspan="8">25</td><td rowspan="2">20</td><td rowspan="11">0</td><td>228</td><td>1300</td><td>22367</td><td>0</td></tr>
<tr><td>H15</td><td>241</td><td rowspan="5">0</td><td>329</td><td>1200</td><td>18237</td><td>0</td></tr>
<tr><td>H16</td><td rowspan="3">150</td><td>105</td><td rowspan="3">0</td><td>315</td><td>1050</td><td>15413</td><td>0</td></tr>
<tr><td>H17</td><td>102</td><td>268</td><td>1000</td><td>15362</td><td>0</td></tr>
<tr><td>H18</td><td>114</td><td>356</td><td>1100</td><td>14137</td><td>0</td></tr>
<tr><td>H19</td><td>262</td><td rowspan="3">130</td><td rowspan="3">20</td><td>308</td><td>1200</td><td>18603</td><td>170</td></tr>
<tr><td>H20</td><td>283</td><td rowspan="2">130</td><td>10</td><td>10</td><td>337</td><td>1400</td><td>23718</td><td>670</td></tr>
<tr><td>H21</td><td>203</td><td rowspan="4">0</td><td rowspan="4">0</td><td>337</td><td>1300</td><td>20468</td><td>0</td></tr>
<tr><td>H22</td><td rowspan="3">150</td><td>88</td><td>107</td><td rowspan="3">0</td><td rowspan="3">0</td><td>300</td><td>1100</td><td>16678</td><td>0</td></tr>
<tr><td>H23</td><td>398</td><td>23</td><td rowspan="2">0</td><td>329</td><td>900</td><td>12168</td><td>0</td></tr>
<tr><td>H24</td><td>150</td><td>20</td><td>480</td><td>800</td><td>8039</td><td>0</td></tr>
</table>

The total operational cost obtained for first case from Table 1 is **$557037** and for case two from Table 2 is **$490496**. Comparing the total operational costs obtained as elaborated through Table 1 and Table 2.

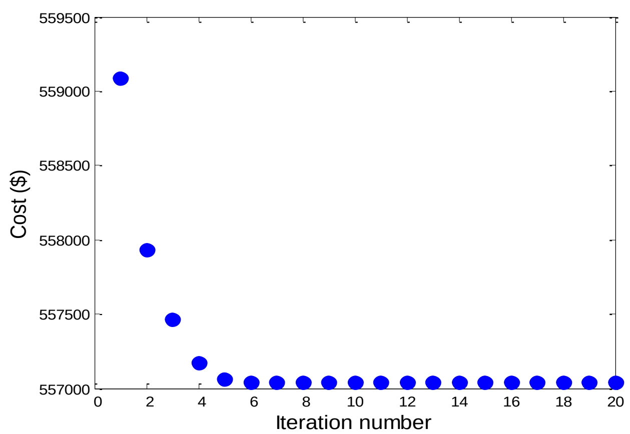

Fig. 2 Convergence for Thermal Unit Commitment Problem

It is evident that the proposed technique demonstarted a saving of **$66541** per day.
The convergence of the proposed method for both the cases is shown in Fig. 2 and Fig. 3 respectively.

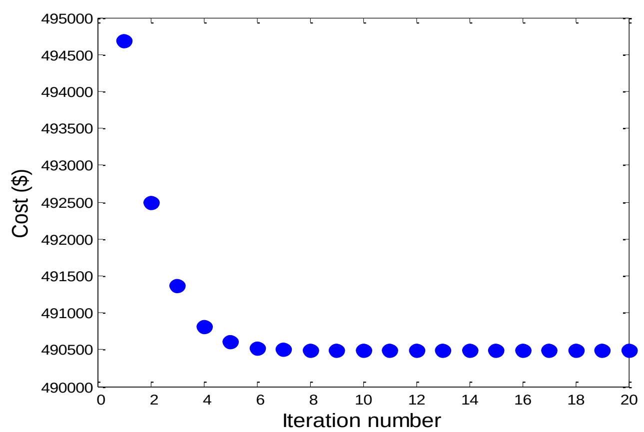

Fig.3 Convergence for Thermal Unit Commitment Problem with BES Integrated WES

The utilization of available wind power in direct dispatch and in charging of the battery is shown in Fig.4. The hourly SOC of battery is shown in Fig.5.

The overall generation including BES integrated WES with thermal generation is shown in Fig.6.

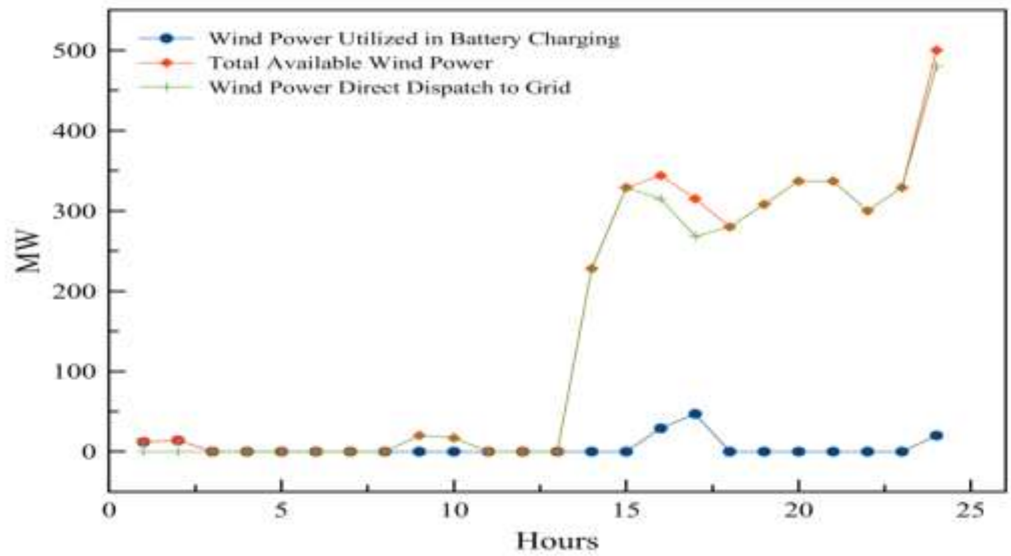

Fig.4 Wind power utilization

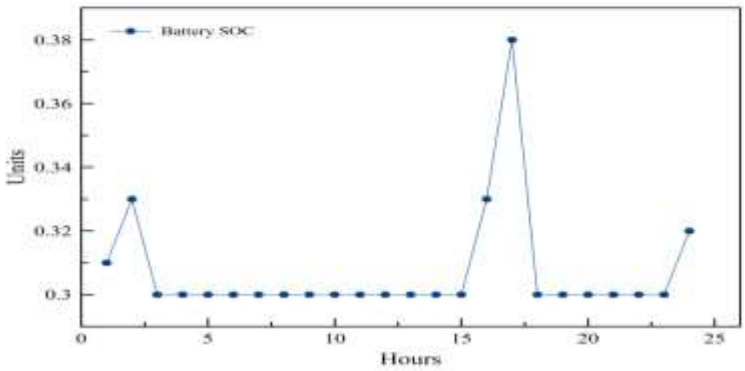

Fig.5 Battery SOC

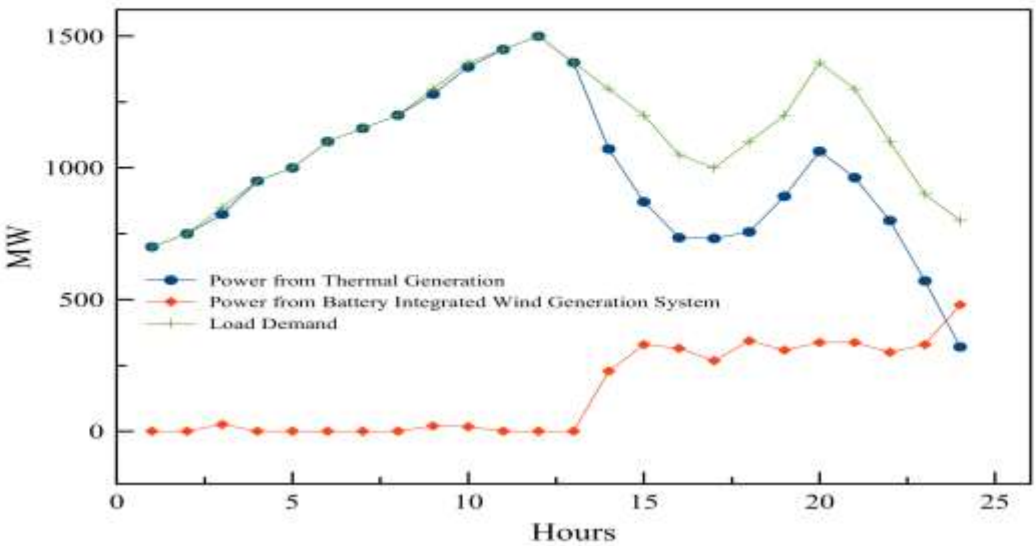

Fig.6 Total Generation Scenario

5. Conclusion

The hybridization of PLM with PSO_TVAC technique was applied to solve the deterministic Unit Commitment Problem of a thermal generation system comprising of ten units operating over a period of 24 hours and the optimum cost was obtained. Thereafter, BES integrated WES was included with existing thermal generators in an optimized manner to get the most optimum cost of operation to meet the same load demand. It is evident from the obtained results that overall generation cost of thermal generators got significantly reduced by about **12%**. Further, it is observed that with the given load profile and the availability of wind generation, the revised thermal generation corresponding to the second peak of load demand gets significantly reduced. This shows that the burden on thermal generation during evening hours can be reduced by optimizing the schedule of battery integrated wind energy system.

Appendices

Appendix 1. Information of Thermal Generators [19, 22-25, 31]

TGs	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10
Pmax	455	455	130	130	162	80	85	55	55	55
Pmin	150	150	20	20	25	20	25	10	10	10
a($/h)	1000	970	700	680	450	370	480	660	665	670
b($/MWh)	16.19	17.26	16.60	16.50	19.70	22.26	27.74	25.92	27.27	27.79
c($/MW2h)	0.0008	0.00031	0.002	0.0021	0.00398	0.0072	0.00079	0.00413	0.0022	0.00173
MD(h)	8	8	5	5	6	3	3	1	1	1
MU(h)	8	8	5	5	6	3	3	1	1	1
HSc($/h)	4500	5000	550	560	900	170	260	30	30	30
CSc($/h)	9000	10000	1100	1120	1800	340	520	60	60	60
Cs(h)	5	5	4	4	4	2	2	0	0	0
Initial Status	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Appendix 2. Day Ahead Load Profile [19, 22-25, 31]

Hours	Hr1	Hr2	Hr3	Hr4	Hr5	Hr6	Hr7	Hr8	Hr9	Hr10	Hr11	Hr12
Load (MW)	700	750	800	950	1000	1100	1150	1200	1300	1400	1450	1500
Hours	Hr13	Hr14	Hr15	Hr16	Hr17	Hr18	Hr19	Hr20	Hr21	Hr22	Hr23	Hr24
Load (MW)	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

Appendix 3. Hourly Wind Speed (WS) Details [22, 24-25]

Hours	Hr1	Hr2	Hr3	Hr4	Hr5	Hr6	Hr7	Hr8	Hr9	Hr10	Hr11	Hr12
WS(m/s)	3.5	3.6	1.5	1.4	0.1	1.8	1.3	2.2	3.8	3.7	2.0	0.6
Hours	Hr13	Hr14	Hr15	Hr16	Hr17	Hr18	Hr19	Hr20	Hr21	Hr22	Hr23	Hr24
WS(m/s)	0.4	8.4	9.9	10.1	9.7	9.2	9.6	10	10	9.5	9.9	12.6
Cut-in speed (m/s)	03											
Cut-out speed (m/s)	25											
Rated speed (m/s)	12											

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