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Optimal Dynamic Dispatch of Wind Integrated Thermal Generators with Compressed Air Energy Storage

Akanksha Bhatt, Manjaree Pandit‡, Aayush Shrivastava, Hari Mohan Dubey

Department of Electrical Engineering, M.I.T.S., Gwalior, India

(akankshabhatt07@gmail.com, manjaree_p@hotmail.com, mr.aayushshrivastava@gmail.com, harimohandubeymits@gmail.com)

‡ Corresponding Author; Manjaree Pandit, Department of Electrical Engineering, M.I.T.S., Gwalior, India, Tel: +91-0751-2409380, Fax: +90 312 123 4567, manjaree_p@hotmail.com

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Abstract- Maintaining reliability of power supply is a big challenge when renewable energy sources (RES) are integrated in the traditional power grid. Allocation of adequate storage of energy is essential in order to maintain power balance with changing demand levels and uncertain and intermittent renewable power generation. After the Kyoto protocol on climate change there is global focus on limiting emissions from fossil fuels. As a result increasing number of RES is being integrated with existing power grids. Their intermittent and uncertain nature however creates difficulty in maintaining reliability particularly when large scale integration of these resources is planned. Efficient energy storage systems are therefore essential to store surplus power when renewable generation is in abundance and to release it during periods when renewable generation is insufficient. This paper explores the viability of operating wind farm coupled with compressed air energy storage (CAES) system to meet the demand in a reliable manner and control the electricity prices during peak loads. The optimal dispatch of thermal units is computed using an improved particle swarm optimization (PSO) such that all thermal, wind generator and CAES system constraints are satisfied. A 24-hour dispatch period is considered by applying thermal generator ramp-rate limits between consecutive time periods. Two separate models are employed for optimizing cost and profit. The proposed method is tested on a test power system consisting of six thermal generating units integrated with 50 wind turbines.

Keywords Compressed air energy storage (CAES), renewable energy sources (RES), profit maximization, cost minimization, wind energy integration, particle swarm optimization, optimal dispatch

1. Introduction

Depleting fossil fuel reserves combined with growing concerns about environmental degradation have brought a surge of large scale integration of renewable energy resources into the power system, prominent among them being wind and solar resources. Increasing penetration of renewable energy resources and their intermittent nature present a major problem for electrical power system operators and planners. Dedicated research and sophisticated approaches are needed to handle the power system operation problems under uncertain and unpredictable renewable generation. In such power systems, shortage or surplus of energy may be experienced frequently due to variations in load/ renewable resource or faults and failures. The most important issue is to maintain the power match between demand and generation in real time. This problem is more prominent for isolated power grids where there are no interconnections. The demand fluctuation normally requires frequent starting/shutting down of conventional thermal or hydro units. The slow ramp up/down capacity of thermal units are major deterrents and hydro units may not be sufficient to meet the shortages [1]. Adequate energy storage facilities are therefore essential to make inclusion of renewable resources viable on a large scale. The significant quantity of renewable energy inclusion in power grids requires a reformulation of the classical economic dispatch (ED) [2, 3] problem to take into account the uncertainty constraints of wind and solar energy and its effect on power system reliability and economics [4].

Therefore research is now focused on the ED problem with emphasis on issues arising due to the incorporation of renewble energy. The main issues addressed in literature are i) multi-objective optimal cost/emission dispatch models [5-11] ii) wind power uncertainty cost models [12-13] iii) Isolated verses utility owned wind power models [14] iv) Spinning reserve requirements [15] v) role of various energy storage methods [16-30] and vi) developing innovatiove stochastic solution algorithms [5-11,21]. This paper explores the effect of the fourth issue on the ED problem and evaluates the impact compressed air energy storage system (CAES) on the cost and profit of power system having wind units. An improved PSO approach, which is a nature inspired stochastic optimization algorithm, is used to compute the ED solution with CAES.

The static wind-thermal dispatch problem has been solved by employing cost and emission minimization objective [5-8]. The dynamic approach is adopted in [9-11]. Powerful stochastic methods like PSO [5], gravitational search [8], artificial bee colony [9], Plant Growth Simulation Algorithm [10] and Quantum genetic algorithm [7,11] are used.

The importance of energy storage technology and its growing need has been evident for some time now. Integration of energy storage technologies with renewable power resources becomes essential to provide a reliable base load power supply capable of providing supply-load balance under varying operating conditions. Systems like flywheel, CAES, pumped hydro storage, batteries, superconducting magnetic energy storage, capacitors and super capacitors etc are used for this purpose. A comprehensive review of the various traditional and future storage techniques for large-scale integration with renewable energy resources in [16-18]. Reference [19] explores the potential of energy storage in the U.S. Financial viability of energy storage system integrated with large wind farms is investigated in [20]. Micro-grids house storage devices to maintain uninterruptible power supply. The optimal battery sizing problem for microgrids is presented in [21]. Hybrid and smart energy storage technologies for the future requirements are reviewed in [22].

Locating CAES near wind farms increases transmission utilization and decreases costs as compared to CAES near the load end [23]. The CAES can be integrated with wind energy coupled with diesel power plants to reduce electricity cost and harmful green house gases emitted from these plants [24]. The operating cost of a gas-fired power wind integrated plant can be reduced by 6.7% and 43% higher profit is obtained when coupled with CAES [25].The combined optimization of a wind/CAES base load plant results in transmitting more wind power at a lower cost as compared to a wind farm without storage [26]. In [27] the cost/revenue of integrating CAES is evaluated and compared with other storage options. A techno-economic study is conducted in [28] to find the costs and social benefits associated with a wind/CAES system. The effect of CAES on prices is analysed in [29] and a cost-benefit analysis of wind-CAES using stochastic wind/demand models and probabilistic optimal power flow is avaialble [30].

This paper presents a dynamic economic dispatch model for wind-thermal power system with CAES. Two models for optimizing cost and profit are employed with large number of equality/inequality constraints. An efficient PSO model is used to solve this complex mixed integer non-linear programming problem.

2. Problem formulation

The dynamic wind-thermal optimal dispatch with CAES is presented here. To analyse the effect of storage on cost and profit, two models are considered.

2.1. Dynamic Dispatch for Profit Maximization

The objective is to compute the optimal dynamic dispacth for maximizing profit given by Pro_max as expressed below:

$$\begin{aligned}Pro\_max = &\sum_{t=1}^{T}[\sum_{i=1}^{N_t} P_{th}(i,t)\,lm_e(t) + \sum_{j=1}^{N_c} P_{CAES}(j,t)\,lm_e(t) + \sum_{k=1}^{N_w} P_w(k,t)\,lm_e(t)]\\ &-\sum_{t=1}^{T}[Cost_{th}(t) + Cost_c(t)]\end{aligned} \tag{1}$$

$$Cost_{th}(t) = \sum_{i=1}^{N_t}[a(i)P_{th}(i,t)^2 + b(i)P_{th}(i,T) + c(i) \tag{2}$$

$$Cost_c(t) = \sum_{j=1}^{N_c} P_{c,p}(j,t)\,lm_e(t) \tag{3}$$

For the tth time instant: Pth(i,t) represents the power output of ith thermal unit, Pw (k, t) and PCAES (j,t) give the output of kth wind generating unit and jth CAES unit, lmet is the forecasted energy price, Costth (t) and Costc(t) give the total fuel cost for thermal units and CAES systems respectively. Pc,p(j,t) shows the power consumed by the jth CAES unit for compressing and injecting air.The number of thermal, wind and CAES units is taken as Nt, Nw and Nc respectively.

2.2. Cost Minimization

Second objective for this paper is to compute optimal dispatch schedule of thermal units such that the fuel cost minimization. The objective function is given by

$$\begin{aligned}Cost\_min = &\sum_{i=1}^{N_t}[\{a(i)P_{th}(i,t)^2 + b(i)P_{th}(i,T) + c(i)\}\\ &+ Cost_C(t)]\end{aligned} \tag{4}$$

The cost coefficients of the i^{th} thermal unit are a(i), b(i) and c(i) respectively.The above two models for profit/cost optimization are subject to constraints listed below.

2.3. Power balance constraints

Maintaining a continuous balance between avaialble power and load is mandatory for a stable power system operation. Therefore the power balance equality constraint is given here for demand represented as PD (t).

$$\sum_{i=1}^{N_t} P_{th}(i,t) + \sum_{j=1}^{N_c} P_{CAES}(j,t) + \sum_{k=1}^{N_w} P_W(k,t) = PD(t) + \sum_{j=1}^{N_c} P_{c.p.}(j,t) \tag{5}$$

2.4. Dynamic Inequality constraints of thermal generating units

Practically a thermal unit has up and down ramp limits that change the min/max range of decision variable Pth for every time instant as given in Eq.(7).

$$P_{th}^{min}(i) \le P_{th}(i,t) \le P_{th}^{max}(i) \tag{6}$$

$$P_{th}(i,t-1) - rrl^{D}(i) \le P_{th}(i,t) \le P_{th}(i,t-1) + rrl^{U}(i) \quad \forall i \tag{7}$$

For the ith steam unit : $P_{th}^{min}(i)$ and $P_{th}^{max}(i)$ represent lower/upper bounds of ith steam unit operation, rrl^{U} and rrl^{D} show the ramp down and up limits respectivly of ith steam generator unit.

2.5. Constraints of wind power generation

The generated wind power is found from forecast wind veclovity as given below:

$$P_{w}(k,t) = \begin{cases} 0 \; ; & \text{if } V_{WS}(k) < V_{ci}(k), V_{WS}(t) > V_{co}(k) \\ P_{WG\max}(k) * \left(\dfrac{V_{WS}(t) - V_{ci}(k)}{V_{r}(k) - V_{ci}(k)} \right)^{3} ; & \text{if } V_{ci}(k) \le V_{WS}(t) \le V_{r}(k) \\ P_{WG\max}(k); & \text{if } V_{r}(k) \le V_{WS}(t) \le V_{co}(k) \end{cases} \tag{8}$$

For the k^{th} wind turbine: P_{WGMAX} (k) represents the rated output, V_{ci} (k) and V_{co} (k) give cut in and cut out speed respectively, and V_{r} (k) is rated wind turbine speed. V_{WS} (t) shows forecasted wind speed at time interval t.

2.6. Equality/inequality constraints for CAES storage unit operation

The CAES systems make use of natural structures like abandoned mines, salt caverns or tanks etc for storing pre-compressed air (with pressures as high as 80 bar) using low cost power during light load periods. Normally almost 2/3 of the fuel consumption goes into compressing and injecting air in the storage. Instead, the CAES system here uses surplus wind energy which is very cleap. During peak load periods, air is drawn from the storage, heated with gas and then fed to a gas turbine. As the compression and generation are separate a considerable amount of fuel is saved. If Vinj (j,t) and Vp (j,t) represent the energy equivalent of air compressed and air injected respectively from/into the jth storage unit at time interval t and the efficiency of injected and pumped power is η_j^{inj} and η_j^{P} respectively then

$$V^{inj}(j,t) = \eta_j^{inj} P_{c.p.}(j,t) \qquad j = 1 \ldots\ldots N_c \tag{9}$$

$$P_{CAES}(j,t) = \eta_j^{P} V^{P}(j,t) \quad \forall j \tag{10}$$

The injected air in the j^{th} storage unit at instant t, $V_{inj}(j,t)$ should be between the minimum/maximum limits $V_{min}^{inj}(j)$ and $V_{max}^{inj}(j)$.Similarly the pumped air $V_p(j,t)$ also must be between lower/upper limits $V_{min}^{P}(j)$ and $V_{max}^{P}(j)$. The CAES unit can not be in the air injection and pumping mode at the same time. This constraint is realized by using a binary variable u^{inj} (j,t)and $u^{P}(j,t)$ such that

$$u^{P}(j,t) + u^{inj}(j,t) \le 1 \tag{11}$$

$$V_{min}^{inj}(j)\, u^{inj}(j,t) \le V^{inj}(j,t) \le V_{max}^{inj}(j)\, u^{inj}(j,t) \tag{12}$$

$$V_{min}^{P}(j)\, u^{P}(j,t) \le V^{P}(j,t) \le V_{max}^{P}(j)\, u^{P}(j,t) \tag{13}$$

The amount of stored energy in the jth storage unit at instant t, A(j,t) should be between the minimum/maximum storage capacity limits $A^{min}(j)$ and $A^{max}(j)$.

$$A^{min}(j) \le A(j,t) \le A^{max}(j) \tag{14}$$

The amount of the stored air is updated every hour as

$$A(j,t+1) = A(j,t) + v^{inj}(j,t) - v^{P}(j,t) \tag{15}$$

3. Implementation by using Improved Particle Swarm Optimization (PSO)

In this paper an improved PSO approach is used for solving the above dynamic wind-thermal dispatch model with CAES. PSO is a population based stochastic optimization technique proposed by Kennedy and Eberhart [31], which is used to find the dispatch solution for cost and profit optimization. It is motivated by flocking of birds when the swarms are searching for food. The population consists of a number of random solutions to the problem which are iteratively improved using a fitness function (cost/profit). One solution of the population, i.e. s^{th} member consists of a matrix of size [T x (Nt+Nw+Nc)] given by

$$\text{Population}_s = \sum_{t=1}^{T}\sum_{i=1}^{N_t}\sum_{j=1}^{N_w}\sum_{k=1}^{N_c} \begin{Bmatrix} P_{th}(i,t), P_{w}(j,t), \\ P_{CAES}(k,t), P_{c,p}(k,t), u^{inj}(k,t), u^{P}(k,t) \end{Bmatrix} \tag{16}$$

3.1. Mechanism of position update

The population consisting of number of solutions is updated in every iteration using the distance of the sth solution from its best local solution and the global best solution known as pbests and gbest respectively as given below[31]

$$V_s^{m+1} = w V_s^{m} + c_1 \, rand_1(\ldots.) * (pbest_s - s_s^{m}) + c_2 \, rand_2(\ldots..) * (gbest - s_s^{m}) \tag{17}$$

$$\text{Population}_s^{m+1} = \text{Population}_s^{m} + v_s^{m+1} \tag{18}$$

Where, v_s^{m} represents velocity of s^{th} population member at m^{th} iteration, w and c1, c2 show the inertia weight and acceleration coefficients respectively. rand represents uniformly distributed random number between 0 and 1. S_s^{m} gives current position of s^{th} member at m^{th} iteration.

3.2. Time-varying inertial weight and acceleration coefficients

The inertia weight varies iteratively in PSO between w1 and w2 which are normally taken as 0.9 and 0.4 respectively. Weight function of the problem is

$$w = (w1 - w2) \times \frac{(\text{maxit} - \text{iter})}{\text{max it}} + w2 \tag{19}$$

Where, w1 and w2 represents initial and final weight respectively, maxit and iter represent the maximum and current iteration number respectively. To improve the performance time-varying acceleration coefficients are employed as shown below [32]: These are substituted in Eq. (17) for computing the veclocity. Here $c_{1initial}$, c_{1final}, $c_{2initial}$ and c_{2final} are initial/final values of acceleration factors c1/ c2 respectively.

$$v_s^{m+1} = w \times v_s^m + \left(\left(c_{1,final} - c_{1,initial} \right) \frac{iter}{\max it} + c_{1,initial} \right) \times rand_1 \times (pbest_s - S_s^m) + \left(\left(c_{2,final} - c_{2,initial} \right) \frac{iter}{\max it} + c_{2,initial} \right) \times rand_2 \times (gbest_s - S_s^m) \quad (20)$$

4. Results and discussion

In this paper, two models to optimize profit and cost function of the dynamic wind-thermal power system with CAES are employed. There are complex constraints and continuous as well as binary variables; therefore an improved particle swarm optimization (PSO) technique is employed for solving this optimization problem. To observe the effect of CAES on system performance, the cost and profit models are evaluated for cases with and without storage.

4.1. Description of the Test Systems

The improved PSO approach for dynamic wind-thermal dispatch integrated with storage is tested on first 6 thermal units of the IEEE 118 bus test system with 54 thermal generating units. The data is listed in Table 1[33]. The data for the 50 identical wind generating units of E-70 E4 model from ENERCON is listed in Table 2 [34]. The data for CAES unit is tabulated in Table 3.

The forecast wind speed for a typical day is given in Fig. 1. Fig. 2 shows the variation of the wind power output and power demand with time. Fig. 3 gives plot between forecasted prices with time. Wind power output can be calculated using Eq. (8). Fig. 4. shows the forecasted price of energy ($/MW) with time. The simulations were carried out using MATLAB R 2009 on a latest Pentium processor with 2 GB RAM

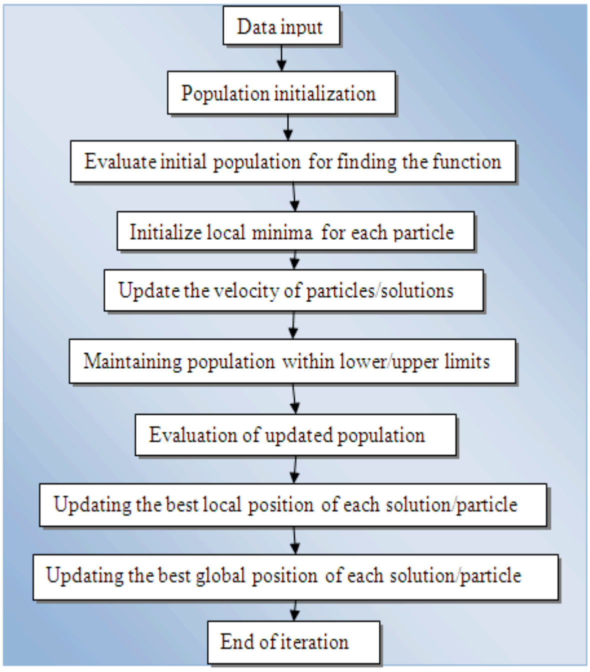

Fig. 1. Flow chart of particle swarm optimization technique

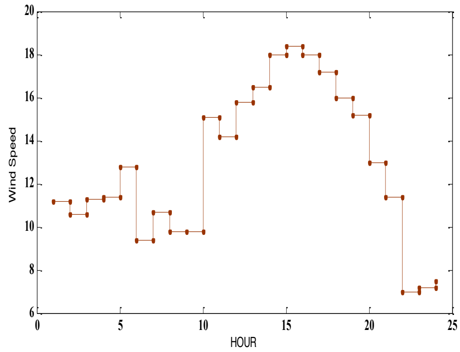

Fig. 2. Variation of wind speed (m/s) with time (hour)

Table 1. Conventional thermal generator units Characteristics

	P_{min}/P_{max}	a(i)	b(i)	c(i)	e(i)	f(i)	Rrl^U/rrl^D
1	5/30	0.0697	26.2438	31.67	75	0.05	15/15
2	5/30	0.0697	26.2438	31.67	75	0.05	15/15
3	5/30	0.0697	26.2438	31.67	75	0.05	15/15
4	150/300	0.0109	12.8875	6.78	315	0.05	150/150
5	100/300	0.0109	12.8875	6.78	315	0.05	150/150
6	10/30	0.0697	26.2438	31.67	130	0.05	15/15

Table 2. Wind Turbine Specifications

V_c (m/s)	V_r (m/s)	V_{co} (m/s)	P_{WGmax} (MW)
2	14	25	2.05

Table 3. Specifications of CAES unit in MWh

A^{min}	A^{max}	V_{min}^{inj}	V_{max}^{inj}	V_{min}^{p}	V_{max}^{p}
50	500	5	50	5	50

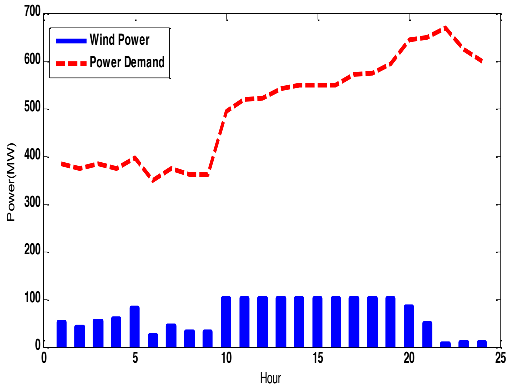

Fig. 3. Hourly wind power output and power demand

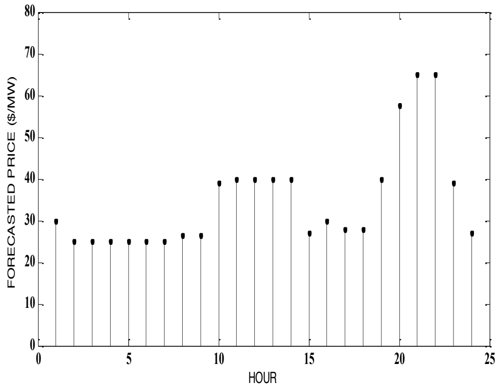

Fig. 4. Variation of forecasted price ($/MW) with time (hour)

4.2. Dynamic wind-thermal dispatch for profit maximization

1) Case 1: Profit maximization without CAES

The optimal dynamic dispatch is carried out to maximize the profit given by Eq. (1) subject to thermal and wind unit constraints given by Eq.(5)-Eq.(8). Storage is not considered therefore CAES unit constraints are not applicable. Table 4 presents the results of optimal dynamic dispatch of all six thermal generators. The results fulfil ramp rate limits and produce optimal profit. Table 5 shows the comparison between PSO and SQP (from MATLAB fmincon solver).and it can be seen that the results are quite close.

2) Case 2: Profit maximization with CAES

Optimal dispatch is carried out for optimizing profit as in case 1 above but additional storage constraints given in Eq.(9)-Eq. (15) are imposed. The results of optimal dispatch are given for 24-hour period in Table 6. The complete dispatch along with injected air and pumped air values are also shown. It can be seen that all the constraints are met. The total profit is found to increase by using storage system from $241071.9 to $266978.2. There is an increase in profit by $ 25906.3 per day. Fig. 5 represents the hourly comparison of optimal profit with and without CAES storage.

4.3. Dynamic wind-thermal dispatch for cost Optimization

1) Case 1: Cost minimization without CAES

The function given by Eq. (4) is minimized subject to all thermal and wind unit constraints given by Eq. (5)-Eq. (8) the cost of thermal generators without using CAES storage. Table 7 gives the optimal schedule of thermal and wind units which can be seen to follow ramp rate limits and all other equality and inequality constraints for every hour in a day. The optimal cost is found to be $198010.6/day.

2) Case 2: Cost minimization with CAES

This test system considers CAES storage including storage level constraints integrated with thermal and wind unit constraints. Table 8 represents optimal dispatch of all units along with injected and pumped air for every hour. The total cost reduced to $182184.9674 from $198010.6 which amounts to a saving of $15825 per day due to integration of CAES storage. Figure 6 shows the hourly computed optimal cost with and without storage.

4.4. Statistical analysis

As PSO is a population based optimization method, its performance depends on population size. Figure 7 shows the variation of minimum, mean and maximum cost with population size. A population size of 250 was found to be suitable for giving the best results.

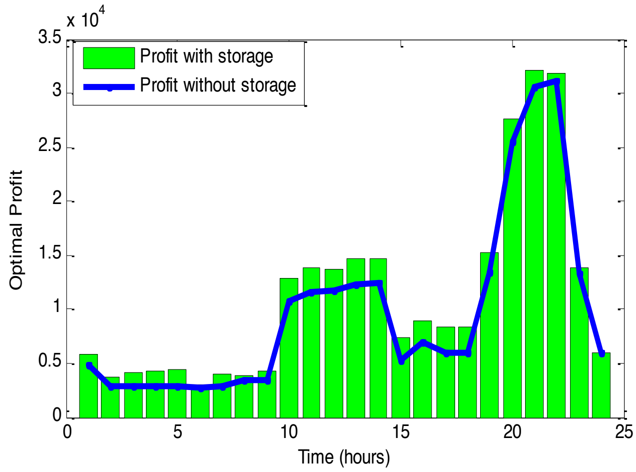

Fig. 5. Hourly comparison profit with and without storage

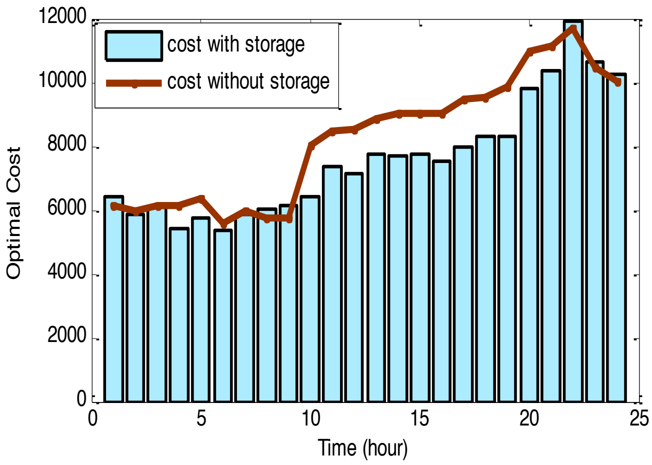

Fig. 6. Hourly comparison of cost with and without storage

Table 4. Optimal dynamic dispatch for profit maximization without storage

Time (Hour)	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	P5 (MW)	P6 (MW)	Profit($)
1	6.5948	5.2876	5.0000	181.5689	171.5522	14.0726	5343.8804
2	5.3569	5.7765	8.5566	165.1768	170.4717	18.9069	3225.2437
3	14.9111	6.2399	5.0000	211.6383	134.3695	11.8870	3311.3911
4	5.0000	9.2085	5.2182	197.7950	144.6469	12.1460	3319.6219
5	6.5236	5.0000	5.0000	206.6355	159.1916	13.6549	3503.1735
6	6.9018	10.2015	6.5959	179.9518	131.6441	14.2242	3029.8814
7	5.0000	8.6418	15.8293	150.0000	184.7477	10.0000	3237.1127
8	5.9685	7.7058	8.1556	216.8550	112.9521	10.3000	3700.3688
9	17.0624	8.7555	5.5961	187.5456	131.4290	11.5485	3619.9029
10	7.2956	12.9547	6.2688	216.0814	229.9396	19.1599	11041.0867
11	16.8103	19.2481	5.7964	248.0447	216.5358	11.5147	12034.0375
12	7.6049	10.1116	12.5351	238.2866	239.9974	10.6644	12177.9066
13	9.5271	10.1958	7.6497	245.5762	255.6312	10.0000	12648.2162
14	8.7789	9.8068	5.1956	282.6647	231.5040	10.0000	12870.1200
15	16.1597	6.6467	7.9664	205.8527	299.9923	11.3322	5604.9989
16	5.3325	10.5898	10.6511	208.8539	299.5427	12.9799	7286.0237
17	5.4650	13.3973	20.7288	259.5689	260.6600	10.0000	6340.4439
18	8.5829	7.6527	8.7535	283.1289	252.4732	12.3589	6471.6516
19	5.0000	9.8088	5.5016	256.1732	300.0000	15.2164	13785.2776
20	10.6191	16.5298	5.0220	300.0000	300.0000	10.0000	26039.5255
21	15.7000	6.8954	9.0291	300.0000	300.0000	17.3901	31082.6270
22	13.9502	21.8954	21.3061	300.0000	300.0000	11.4500	31746.8836
23	6.6004	15.9339	6.3061	300.0000	273.8287	22.1641	13641.1342
24	16.4702	7.2496	9.2559	256.8269	300.0000	10.0000	6011.3577
Total Profit($)							241071.9

Table 5. Comparison of profit without storage between PSO and SQP

Time	PSO	SQP	Time	PSO	SQP	Time	PSO	SQP
1	5343.8804	5343.8860	9	3619.9029	3619.9099	17	6340.4439	6340.4489
2	3225.2437	3225.2497	10	11041.0867	11041.0887	18	6471.6516	6471.6526
3	3311.3911	3311.3917	11	12034.0375	12034.0395	19	13785.2776	13785.2779
4	3319.6219	3319.6289	12	12177.9066	12177.9076	20	26039.5255	26039.5262
5	3503.1735	3503.1755	13	12648.2162	12648.2166	21	31082.6270	31082.6284
6	3029.8814	3029.8834	14	12870.1200	12870.1205	22	31746.8836	31746.8845
7	3237.1127	3237.1157	15	5604.9989	5604.9991	23	13641.1342	13641.1350
8	3700.3688	3700.3688	16	7286.0237	7286.0247	24	6011.3577	6011.3581

Table 6. Optimal dynamic dispatch for maximum profit with storage

Time	P1(MW)	P2(MW)	P3(MW)	P4(MW)	P5(MW)	P6(MW)	Storage $\sum A_i$(MW)	Pumped Air(V^p)	Injected air(V^{inj})	Optimal Profit
1	14.4120	21.5304	9.5769	177.1624	106.3467	10.0063	50.000	0.0000	5.4287	5773.2869
2	5.0000	24.1808	11.7938	166.6341	104.3005	16.8847	55.4287	5.3221	0.0000	3731.3432
3	12.3309	9.7662	5.3451	197.2107	100.3302	10.8800	50.1066	0.0000	5.0000	4083.3511
4	16.0579	5.0000	7.9109	150.0000	121.7272	11.4569	55.1066	5.0000	0.0000	4231.9625
5	19.2489	12.4720	15.3572	150.0000	107.1003	12.8191	50.1066	0.1066	0.0000	4477.1147
6	25.3925	13.9412	5.0000	150.2678	127.7019	14.1523	50.000	0.0000	9.0597	2994.4584
7	5.0000	16.2435	5.0000	168.4953	113.7874	14.6500	59.0597	9.0597	0.0000	4036.2173
8	6.7930	5.7678	14.1492	208.6057	100.0000	10.0087	50.000	0.0000	13.0053	3915.4181
9	6.1931	5.0000	6.8568	196.1567	100.0000	11.4136	63.0053	5.9367	0.0000	4330.8777
10	7.4020	11.8056	10.9437	189.9362	155.2393	10.9233	57.0686	5.0000	0.0000	12903.5046
11	14.5020	5.4834	14.9428	201.4831	161.9699	17.0502	52.0686	2.0686	0.0000	13830.6255
12	10.1184	6.3941	5.4409	192.8967	200.4867	19.3581	50.000	0.0000	15.9449	13673.9901

Table 6. Optimal dynamic dispatch for maximum profit with storage (cont.)

13	10.0445	5.2344	5.0000	195.7794	204.6512	10.5430	65.9448	6.8775	0.0000	14622.7867
14	20.2470	8.1488	5.0000	207.6124	188.9772	12.5146	59.0673	5.0000	0.0000	14638.9020
15	16.4556	6.6244	9.5922	182.9715	205.6148	22.1744	54.0673	4.0673	0.0000	7374.1180
16	8.4476	14.9088	5.0000	227.2248	190.6008	12.3668	50.000	0.0000	11.0487	8914.6726
17	7.7579	5.7772	6.3392	239.6572	193.0843	11.7542	61.0487	5.0000	0.0000	8413.7429
18	11.6612	13.5040	5.0000	215.5692	203.8395	16.8774	56.0487	6.0487	0.0000	8316.8450
19	13.6827	8.7359	11.3864	206.0550	237.0460	22.5961	50.000	0.0000	8.2520	15280.8483
20	14.1359	8.6794	6.9904	207.0695	300.0000	16.7000	58.2520	6.8389	0.0000	27629.6518
21	8.0746	15.1301	5.7185	260.2369	299.9972	10.4235	51.4131	1.4131	0.0000	32107.6161
22	11.9280	21.6334	16.4698	300.0000	300.0000	16.4518	50.000	0.0000	5.0000	31808.9353
23	14.2982	13.1702	8.2230	266.0283	295.5374	14.4029	55.0000	5.0000	0.0000	13913.9703
24	6.6956	7.7307	15.4618	300.0000	261.6365	11.5434	50.000	0.0000	12.5820	5973.9635
Total Profit($)										266978.2

Table 7. Optimal dynamic dispatch for minimum cost without storage

Time	P1(MW)	P2(MW)	P3(MW)	P4(MW)	P5(MW)	P6(MW)	Optimal Cost($/h)
1	5.0000	5.0000	5.0003	177.5887	181.4871	10.0000	6138.9129
2	5.0000	5.0000	5.0000	174.6718	174.5735	10.0000	5974.1813
3	5.0000	5.0000	5.0000	178.2959	180.7498	10.0000	6138.3481
4	5.0000	5.0000	5.0000	173.7955	175.2193	10.0000	6138.3481
5	5.0000	5.0000	5.0000	186.4104	184.5950	10.0000	6340.0488
6	5.0000	5.0000	5.0000	163.1093	161.4099	10.0000	5564.7447
7	5.0003	5.0000	5.0000	170.9616	178.2567	10.0000	5974.0306
8	5.0000	5.0000	5.0000	168.5847	168.3523	10.0000	5769.5274
9	5.0000	5.0000	5.0000	170.5058	166.4316	10.0000	5769.6359
10	5.0000	5.0000	5.0000	232.6544	234.0457	10.0000	8010.2027
11	5.0000	5.0000	5.0000	244.3273	248.6226	10.0000	8485.8737
12	6.1446	5.0088	7.4149	245.1820	245.4461	10.0025	8540.2408
13	5.0000	5.0000	5.0000	257.4231	256.1568	10.0000	8864.8187
14	5.0000	5.0000	5.0000	263.1013	259.8486	10.0000	9038.5554
15	5.0000	5.0000	5.0000	259.4780	263.4717	10.0001	9038.5873
16	5.0000	5.0006	5.0000	263.7500	259.1995	10.0000	9038.6169
17	5.0000	5.0000	5.0090	272.7705	272.0399	10.0000	9447.7196
18	5.0000	5.0050	5.0000	274.6066	273.3387	10.0000	9506.6688
19	5.0000	5.0000	5.0000	283.1749	283.5251	10.0000	9862.1403
20	10.7390	10.2840	10.6206	300.0000	300.0000	10.5273	10972.4617
21	12.2792	12.3063	11.8394	300.0000	300.0000	10.5273	11162.9561
22	17.1964	17.1019	17.2299	300.0000	300.0000	17.0731	11717.1222
23	5.0000	5.0000	5.0000	299.8331	300.0000	10.0000	10499.7914
24	5.0000	5.0000	5.0000	286.0099	288.7923	10.0000	10017.0182
Total Cost($)							198010.6

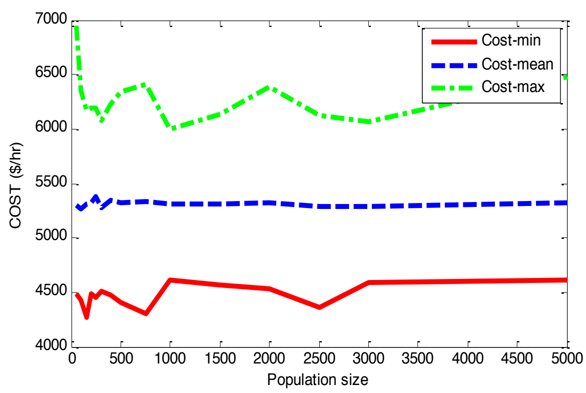

Fig. 7. Statistical analysis for robustness

5. Conclusion

This work focuses on the effect of compressed air energy storage on the cost of operation and profit earned from a wind integrated thermal power system. It has been shown that a significant saving in fuel costs can be achieved by integrating a CAES system to store cheap wind energy during off peak hours. The detailed dynamic dispatch schedule which will produce minimum cost and maximum profit is computed along with air injected in storage and air pumped from storage to thermal units during peak hours. An improved PSO algorithm is used for the complex and constrained mixed integer non-linear programming problem. The results are validated using SQP algorithm and it is shown that all equality and inequality constraints of thermal, wind and CAES system are satisfied.

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Table 8. Optimal dynamic dispatch for maximum cost with storage

Time	P1(MW)	P2(MW)	P3(MW)	P4(MW)	P5(MW)	P6(MW)	V^{inj}	V^{p}	$\sum A_i$	Optimal Cost
1	12.1709	21.0366	20.4380	199.2404	100.0000	15.2963	0.0000	34.5756	50.0000	6438.0233
2	6.7539	6.0525	26.7226	180.5277	109.2209	14.8821	0.0000	10.0445	84.5756	5866.8487
3	5.0000	15.3314	13.5696	175.3590	104.9176	24.2354	0.0000	7.5446	94.6201	6094.3916
4	18.4425	17.9898	5.4560	150.0000	100.0000	20.2645	5.0000	0.0000	102.1647	5424.7004
5	8.0532	16.1932	17.5003	155.3624	111.3496	23.0894	0.0000	14.4441	97.1647	5758.5984
6	9.6579	5.0000	10.7085	152.2586	128.7184	14.3135	6.7420	0.0000	111.6088	5349.7172
7	18.5618	7.1680	17.0612	165.2467	110.5771	20.7374	0.0000	7.1169	104.8668	5876.7100
8	14.1999	7.6709	10.9884	152.0710	158.7891	14.8527	0.0000	26.2550	111.9837	6006.2668
9	22.4123	13.4174	20.5949	155.8850	112.3835	20.4379	0.0000	13.5740	138.2387	6123.7152
10	8.7688	14.1572	12.6554	199.7569	140.4963	10.0000	5.4158	0.0000	151.8127	6409.9617
11	16.6006	8.6369	16.8421	150.0000	219.1504	20.1299	0.0000	13.8613	146.3969	7388.6006
12	9.1855	13.2695	27.3857	163.7017	182.4070	17.7997	5.0000	0.0000	160.2582	7130.3893
13	16.6875	10.8305	28.8771	159.0491	210.2356	18.6790	0.0000	6.2306	155.2582	7770.1705
14	22.8858	11.0549	16.7204	204.8835	161.1709	24.9742	5.8106	0.0000	161.4888	7693.2990
15	15.4338	9.9031	15.7441	185.9820	216.5461	10.6909	0.0000	6.7962	155.6782	7768.9878
16	14.9362	12.1315	5.4628	173.5149	234.8922	11.5618	0.0000	5.0000	162.4744	7530.4797
17	15.6943	14.6150	15.5106	231.0194	170.5032	17.0259	5.0000	0.0000	167.4744	7959.8348
18	19.1156	21.6543	6.3557	168.0482	256.2358	11.7630	0.0000	10.6752	162.4744	8315.9519
19	16.9506	7.6250	15.6845	156.7260	269.0380	18.3078	6.9188	0.0000	173.1496	8289.5586
20	13.2343	19.5709	13.5668	248.5944	267.6597	10.4988	0.0000	12.7095	166.2308	9817.7246
21	11.9967	6.7726	27.8822	300.0000	221.9730	24.6004	7.7698	0.0000	178.9403	10369.9244
22	13.0959	9.8527	25.8324	300.0000	300.0000	25.3620	0.0000	12.6618	171.1705	11923.5094
23	17.7774	7.5828	18.8490	246.3855	300.0000	20.6941	5.3734	0.0000	183.8323	10652.5173
24	13.2299	9.9289	10.6651	281.9988	256.7080	22.9549	0.0000	5.0000	178.4589	10225.0862
Total Cost($)										182184.9674

References

[1] P. Wang, Z. Gao, L. Bertling Tjernberg, “Operational adequacy studies of power systems with wind farms and energy storages “ , IEEE Transl. on Power System 1.

[2] A.J.Wood and B.F.Wollenberg, Power Generation, Operation and Control, New York: Wiley, 1984. (Book)

[3] D.P.Kothari and I.J.Nagrath, Power system engineering, Tata McGraw- Hill, New Delhi 2008. (Book)

[4] Azza A. ElDesouky, “Security and stochastic economic dispatch of power system including wind and solar resources with environmental consideration”, International journal of renewable energy research, Vol.3, No.4, 2013.

[5] C.X. Guo , Y.H. Bai , X. Zheng , J.P. Zhan , Q.H. Wuc, “Optimal generation dispatch with renewable energy embedded using multiple objectives” ,Electrical Power and Energy Systems, vol. 42, pp. 440–447, 2012.

[6] C. Kuo, “Wind energy dispatch considering environmental and economic factors”, Renewable Energy, Vol. 35, Issue10, pp. 2217-2227, October 2010.

[7] J. Lee , W. Lin , G. Liao and T. Tsao, “Quantum genetic algorithm for dynamic economic dispatch with valve-point effects and including wind power system”, Electrical Power and Energy Systems, vol. 33, pp. 189–197, 2011.

[8] S. Mondal , A. Bhattacharya , S. Halder nee Dey, “Multi-objective economic emission load dispatch solution using gravitational search algorithm and considering wind power penetration”, Electrical Power and Energy Systems, vol. 44, pp. 282–292, 2013.

[9] H.T. Jadhav, R. Roy, “Gbest guided artificial bee colony algorithm for environmental/economic dispatch considering wind power”, Expert Systems with Applications, vol. 40, pp. 6385–6399, 2013.

[10] H.T. Jadhav, H. Bhandari, Y. Dalal and R. Roy, “Economic load dispatch including wind power using plant growth simulation algorithm”, IEEE Environment and Electrical Engineering International Conference, pp. 388-393, May 2012. (Conference Paper)

[11] G. Liao, “A novel evolutionary algorithm for dynamic economic dispatch with energy saving and emission reduction in power system integrated wind power”, Energy, vol. 36, pp. 1018-1029, 2011.

[12] J. Hetzer, D. C. Yu, K. Bhattarai, "An economic dispatch model incorporating wind power", IEEE Transactions on Power Systems, Vol. 23, No. 2, pp. 603-611, June 2008.

[13] J. Aghaei , T. Niknam , R. Azizipanah-Abarghooee and J. M. Arroyo, "Scenario-based dynamic economic emission dispatch considering load and wind power uncertainties", Electrical Power and Energy Systems, vol. 47, pp. 351–367, 2013.

[14] C. Lu , C. Chen , D. Hwang and Y. Cheng, "Effects of wind energy supplied by independent power producers on the generation dispatch of electric power utilities", Electrical Power and Energy Systems, vol. 30, pp. 553–561, 2008.

[15] K. De Vos , A. G. Petoussis , J. Driesen and R. Belmans, "Revision of reserve requirements following wind power integration in island power systems", Renewable Energy, vol.50, pp. 268-279, 2013.

[16] H. Chen, T. Ngoc Cong, W. Yang, C. Tan, Y. Li and Y. Ding, "Progress in electrical energy storage system: A critical review", Progress in Natural Science, Vol. 19, Issue 3, pp. 291–312, 10 March 2009.

[17] H. Ibrahim, A. Ilinca, J. Perron, "Energy storage systems—Characteristics and comparisons", Renewable and Sustainable Energy Reviews, Vol. 12, Issue 5, pp. 1221–1250, June 2008.

[18] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications", Renewable and Sustainable Energy Reviews, Vol. 13, Issues 6–7, pp. 1513–1522, August–September 2009.

[19] S. Van der Linden, "Bulk energy storage potential in the USA, current developments and future prospects", Energy, Vol. 31, Issue 15, pp. 3446–3457, December 2006.

[20] D. Zafirakis , K. J. Chalvatzis, G. Baiocchi and G. Daskalakis, "Modeling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy", Applied Energy, vol. 105, pp. 138–154, 2013.

[21] B. Bahmani-Firouzi , R. Azizipanah-Abarghooee, "Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm", Electrical Power and Energy Systems, vol. 56, pp. 42–54, 2014.

[22] X. Tan , Q. Li , H. Wanga, "Advances and trends of energy storage technology in Microgrid", Electrical Power and Energy Systems, vol. 44, pp. 179–191, 2013.

[23] P. Denholm, R. Sioshansi, "The value of compressed air energy storage with wind in transmission-constrained electric power systems", Energy Policy, Vol. 37, Issue 8, pp. 3149–3158, August 2009.

[24] H. Ibrahim, R. Younès, T. Basbous, A. Ilinc and M. Dimitrova, "Optimization of diesel engine performances for a hybrid wind–diesel system with compressed air energy storage", Energy, Vol. 36, Issue 5, pp. 3079–3091, May 2011.

[25] M. Abbaspour , M. Satkin , B. Mohammadi-Ivatloo , F. Hoseinzadeh Lotfi and Y. Noorollahi, "Optimal operation scheduling of wind power integrated with compressed air energy storage (CAES)", Renewable Energy, vol. 51, pp. 53-59, 2013.

[26] S. Succar , D. C. Denkenberger , R. H. Williams, "Optimization of specific rating for wind turbine arrays coupled to compressed air energy storage", Applied Energy, vol. 96, pp. 222–234, 2012.

[27] H. Lund, G. Salgi, "The role of compressed air energy storage (CAES) in future sustainable energy systems", Energy Conversion and Management, Vol. 50, Issue 5, pp. 1172–1179, May 2009.

[28] E. Fertig, J. Apt, "Economics of compressed air energy storage to integrate wind power: A case study in ERCOT", Energy Policy, Vol. 39, Issue 5, pp. 2330–2342, May 2011.

[29] H. Lund, G. Salgi, B. Elmegaard and Anders N., "Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices", Applied Thermal Engineering, Vol. 29, Issues 5–6, pp. 799–806, April 2009.

[30] A. Arabali, M. Ghofrani, M. Etezadi-Amoli, "Cost analysis of a power system using probabilistic optimal power flow with energy storage integration and wind generation", Electrical Power and Energy Systems, vol. 53, pp. 832–841, 2013

[31] J.Kennedy, R. Eberhart, "Particle swarm optimization", in proc. IEEE Conf. on Neural Networks (ICNN'95), vol. IV, Perth, Australia, 1995, pp.1942-1948.

[32] K. T. Chaturvedi, M. Pandit and L. Srivastava, "Self-organizing hierarchical particle swarm optimization for nonconvex economic dispatch", IEEE Transactions on Power Systems, vol. 23, no. 3, 2008, pp. 1079-1087.

[33] [Online]. Available from: motor.ece.iit.edu/data/SCUC_118test.xls, February 2011.

[34] [Online]. Available from: http://www.enercon.de/p/downloads/ENProduktue bersicht0710.pdf, accessed February 2011.