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# Wind-Thermal Energy Dispatch Integrated With Energy Storage Systems(ESS).

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## Abstract

Particle swarm optimization (PSO) algorithm is applied to find optimal dispatch for minimizing cost of thermal and wind generating units integrated with energy storage systems like compressed air energy storage. Wind power generation depends on the wind speed. The wind power is random in cost model considered by taking a practical dynamic dispatch model. This paper considers six thermal generator and wind turbine taken from IEEE 118-bus test system with CAES systems. The model includes thermal generating units' constraints like ramp rate limits and valve point loading (VPL) effects. CAES systems provide better balancing between energy supply and demand. Integration of energy storage systems with thermal and wind generating units makes electrical systems more reliable and more efficient. The capital cost of CAES system becomes much lower compared with other storage technologies like batteries, pumped hydroelectric storage systems etc. Practical constraints lead to non-linear and non-convex optimization problems. Two cases are studied using Particle swarm optimization (PSO) and interior point algorithm. Particle swarm optimization (PSO) reduces the cost in comparison of interior point algorithm.

**Keywords**— cost minimization; valve point loading; ramp rate limits; partical swarm optimization(PSO); compressed air energy storage systems (CAES)

## I. INTRODUCTION

Electricity is essential for modern society. The electric power system has generation, transmission and distribution systems. Electricity can be generated by the renewable and non renewable energy resources. The percentage is given in Fig.1.

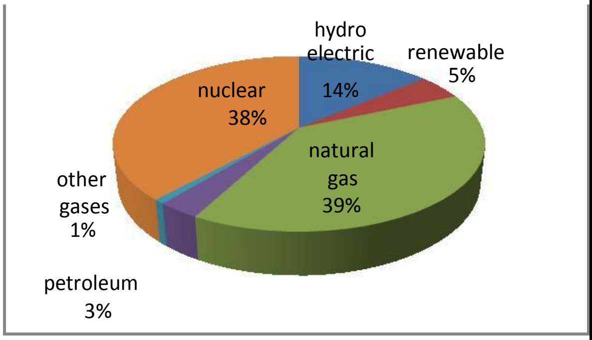

Fig. 1. Percentages of the renewable and non-renewable energy resources.

Energy consumption is depending on the fossil fuels in most of the countries. Electricity can be generated by the conventional and non conventional power plants. Technological options for electrical generation are given in the Table 1. [2]

TABLE I. TECHNOLOGICAL OPTIONS FOR ELECTRICAL GENERATION.

| **Type of power station** | **Primary energy sources** |
|---|---|
| Nuclear | Uranium |
| Fossi-fired steam | Coal, oil, residual oil |
| Hydroelectric | Falling water |
| Combustion turbines | Distillate oil, residual oil |
| Diesel Engines | Diesel fuel |
| Combined cycle | Oil or natural gas |
| Pumped storage | Falling water |
| Steam turbine | Biomass, geothermal |
| Fuel cells | Hydrogen rich gas |
| photovoltaic | solar |
| Wind turbine | wind |

To drive electrical generators, electricity obtained from thermal power plants by burning fossil fuels such as natural gas, coal, oil etc. Renewable energy sources like wind energy, are widely applied to reach

emission reduction with the increasing concern of environmental protection. Environmental protection has been raised recently due to the concerns regarding global weather and air pollution.
The estimation of wind is always a problem. Thus, when wind power is insufficient, the electricity demand will be provided by other sources, such as energy storage systems. Due to random nature of wind, different methods are used with renewable energy generation such as pumped hydroelectric storage[4,5], compressed air energy storage, batteries, including lead acid, nickel cadmium and lithium ion, [8,9] hydrogen storage, capacitors and super capacitors, flywheel and superconducting magnetic energy storage [1].

Energy storage systems (ESSs), based on the use of wind energy surplus, is currently investigated. Among the many energy-storage systems, only pumped storage and CAES systems have the capability for large-scale wind energy integration.

- ESSs provide better balancing between energy supply and demand.
- When energy deficits appear, large-scale energy storage infrastructure that may allow storage of wind energy in excess and feed the grid. [3]
- A large-scale of renewable energy resources can be fed into the grid which will reduce the potential impact on the environment.

## II. COMPRESED AIR ENERGY STORAGE (CAES) SYSTEMS

### *A. Operation principle*

Operation of a typical energy storage systems (ESSs) are based on the principle that when energy excess is available (i.e., when energy demand is lower than supply) the system operates in ‘‘charging’’ mode and stores the surplus of electrical energy in a specific storage media through energy conversion. Energy remains stored in the system until electricity supply fails to cover demand or an economic incentive appears for the ESS to deliver its energy to the grid. At that point, the required amount of energy is drawn from the storage and is converted back to useful electricity so as to serve the demand side. [6,10]

The CAES systems using this principle and storage media in CAES is air. The capital cost of CAES becomes much lower compared with other storage technologies. CAES is the preferable technology compared with pumped hydroelectric storage, lead acid batteries, and vanadium redox batteries in terms of the capital cost. There are more geologically suitable sites for CAES than for the pumped storage system. [2] Some of the compressed air energy storage sites are given in chronological order in Fig. 2. The integration of CAES systems with wind and thermal generating units changed the industrial scenario during the last few decades. And make the electrical system more efficient, robust and user friendly.

## III. PROBLEM FORMULATION

This section provides mathematical formulation. Mathematically formulated cost as an objective function of this paper is-(1)

Where, Costt (t) - the total cost of thermal generation units at

time horizon t [\$/h], Pt(i, t) - the power output of thermal unit i at time horizon t [MW]

### *A. Thermal power constraints are*-2)

Where, Pmin the minimum power output of the thermal generation unit i , Pmax the maximum power output of the thermal generation unit i .

Equation (1) shows total cost using quadratic function. Constraints of real power operation are modeled in equation (2) and ramp rate limits are given in equation (3). Ramp rate limits are a dynamic constraints that complicate the optimized solution.

Fig. 2. CAES: History in chronological order-

### *B. valve point loading (VPL) effect:*

A rectified sinusoidal function is added in the cost function of $i^{th}$ unit for accurate results of VPL effects. A mathematical formulation of the cost function of conventional thermal units with valve point loading (VPL) effects is given.

$$\left| e_i \times \sin\left(f_i \times \left(P_i^{\min} - P_i\right)\right) \right| \quad (4)$$

$e_i$ and $f_i$ are the fuel cost-coefficients of the i^th^ unit of to model VPL effects. Table II gives conventional thermal generator units Characteristics.[6]

TABLE II. CONVENTIONAL THERMAL GENERATOR UNITS CHARACTERISTICS.[6]

| Unit | $P_{min}$ | $P_{max}$ | a(i) | b(i) | C(i) | RU | RD |
|---|---|---|---|---|---|---|---|
| 1 | 5 | 30 | 0.0697 | 26.2438 | 31.67 | 15 | 15 |
| 2 | 5 | 30 | 0.0697 | 26.2438 | 31.67 | 15 | 15 |
| 3 | 5 | 30 | 0.0697 | 26.2438 | 31.67 | 15 | 15 |
| 4 | 150 | 300 | 0.0109 | 12.8875 | 6.78 | 150 | 150 |
| 5 | 100 | 300 | 0.0109 | 12.8875 | 6.78 | 150 | 150 |
| 6 | 10 | 30 | 0.0697 | 26.2438 | 31.67 | 15 | 15 |

### C. Wind power constraints are-

Fig3 and Fig4 shows the variation of the wind speed and wind power output with time respectively. Total generated power can be calculated by using the following equation-

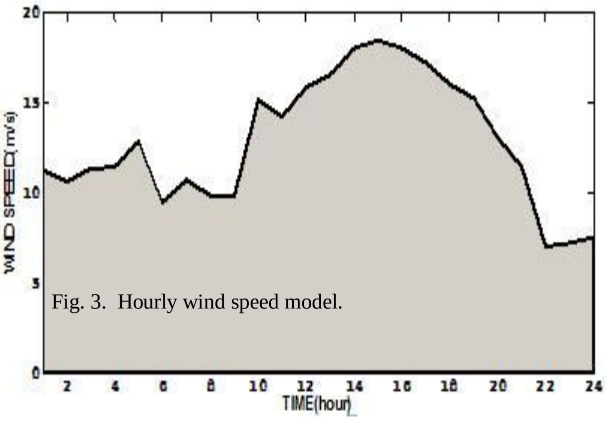

Fig. 3. Hourly wind speed model.

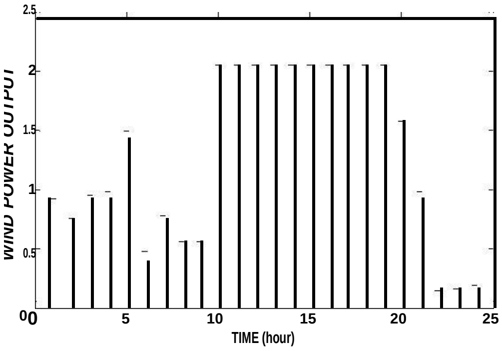

Fig. 4. Variation of wind power output ($/MW) with time (hour).

wind turbine k [m/s]. Parameters of the 2.05 MW wind turbine are given in Table II. [2]

$$P_w(k,t) = \begin{cases} 0 & V_{WS}(t) < V_{cutin}(k), V_{WS}(t) > V_{cutout}(k) \\ P_{WGmax}(k) * \left(\dfrac{V_{WS}(t) - V_{cutin}(k)}{V_{rated}(k) - V_{cutin}(k)}\right)^3 & V_{cutin}(k) \le V_{WS}(t) \le V_{rated}(k) \\ P_{WGmax}(k) & V_{rated}(k) \le V_{WS}(t) \le V_{cutout}(k) \end{cases} \quad (5)$$

TABLE III. PARAMETERS OF THE 2.05MW WIND TURBINE

| $V_{cutin}$(m/s) | $V_{rated}$(m/s) | $V_{cutout}$(m/s) | $P_{WGmax}$(MW) |
|---|---|---|---|
| 2 | 14 | 25 | 2.05 |

## IV. PARTICLE SWARM OPTIMISATION (PSO)

Particle swarm optimization (PSO) is a robust stochastic optimization technique based on the movement and intelligence of swarms. PSO applies the concept of social interaction to problem solving. It was developed in 1995 by James Kennedy (social-psychologist) and Russell Eberhart (electrical engineer).

Each particle keeps track of its coordinates in the solution space which are associated with the best solution (fitness) that has achieved so far by that particle. This value is called personal best, pbest. Another best value that is tracked by the PSO is the best value obtained so far by any particle in the neighborhood of that particle. This value is called gbest.

The modification of the particle’s position can be mathematically modeled according the following equation-

$$Vik+1 = wVik + c1\ rand1(\ldots) \times (pbesti-sik) + c2\ rand2(\ldots) \times (gbest-sik) \tag{6}$$

where, PWGmax(k) -the rated power of wind turbine k [MW] , Vws(t) -the forecasted wind speed at time t [m/s] , Vcutin(k) -the cut in speed of wind turbine k [m/s], Vcutout(k) -the cut out speed of wind turbine k [m/s], Vrated (k) -the rated speed of

where, vik : velocity of agent i at iteration k, w: weighting function, cj : weighting factor, rand : uniformly distributed random number between 0 and 1. sik : current position of agent i at iteration.

The following weighting function is usually utilized in

$$w = wMax-[(wMax-wMin) \times iter]/maxIter \tag{7}$$

where, wMax= initial weight, wMin = final weight, maxIter = maximum iteration number, iter = current iteration number.

TABLE IV. OPTIMAL DISPATCH RESULTS WITH RAMP RATE LIMITS AND VPL EFFECT USING PSO.

| Time | P1(MW) | P2(MW) | P3(MW) | P4(MW) | P5(MW) | P6(MW) |
|---|---|---|---|---|---|---|
| 1 | 5.00 | 5.00 | 5.00 | 196.2107 | 162.8319 | 10.00 |
| 2 | 5.00 | 5.00 | 5.00 | 186.4135 | 162.8318 | 10.00 |
| 3 | 5.00 | 5.00 | 5.00 | 196.2189 | 162.8268 | 10.00 |
| 4 | 5.0000 | 5.0022 | 5.0000 | 186.4031 | 162.5761 | 10.0352 |
| 5 | 5.0000 | 5.0000 | 5.0000 | 208.1753 | 162.8301 | 10.0000 |
| 6 | 8.9287 | 8.2092 | 9.5207 | 150.0192 | 162.8414 | 10.0000 |
| 7 | 5.0000 | 5.0000 | 5.0000 | 186.3789 | 162.8203 | 10.0165 |
| 8 | 5.0000 | 5.0000 | 5.0000 | 150.1596 | 186.7781 | 10.0000 |
| 9 | 5.0000 | 5.0000 | 5.0057 | 174.0993 | 162.8319 | 10.0000 |
| 10 | 6.4657 | 5.4951 | 5.0000 | 213.1296 | 251.6059 | 10.0018 |
| 11 | 5.0000 | 5.0000 | 5.0000 | 267.2870 | 225.6630 | 10.0000 |
| 12 | 5.0000 | 5.0000 | 5.0000 | 268.5359 | 225.6640 | 10.0000 |
| 13 | 9.4425 | 9.5144 | 7.9391 | 275.6909 | 225.9935 | 10.0000 |
| 14 | 11.5607 | 11.0084 | 13.7961 | 275.7616 | 225.8250 | 10.0000 |
| 15 | 17.6510 | 8.1623 | 10.7134 | 275.7424 | 225.6808 | 10.0000 |
| 16 | 9.4148 | 15.8168 | 11.3221 | 275.6839 | 225.6752 | 10.0372 |
| 17 | 5.0000 | 5.0158 | 5.0000 | 275.6376 | 269.1626 | 10.0044 |
| 18 | 5.0000 | 5.0000 | 5.0000 | 275.6632 | 272.2867 | 10.0000 |
| 19 | 5.6618 | 5.1390 | 6.7355 | 275.6671 | 288.4973 | 10.0000 |
| 20 | 14.1468 | 15.8484 | 13.6770 | 300.0000 | 288.4985 | 10.0000 |
| 21 | 21.1414 | 15.1266 | 14.2212 | 300.0000 | 288.4980 | 10.0274 |
| 22 | 18.6459 | 16.8479 | 15.8573 | 299.9952 | 288.5046 | 10.0007 |
| 23 | 5.8980 | 9.6444 | 10.7950 | 300.0000 | 288.4956 | 10.0000 |
| 24 | 8.9683 | 8.6272 | 7.9371 | 275.7280 | 288.5415 | 10.0000 |

TABLE V. OPTIMAL DISPATCH RESULTS WITH RAMP RATE LIMITS AND VPL EFFECT USING INTERIOR POINT ALGORITHM.

| Time | P1(MW) | P2(MW) | P3(MW) | P4(MW) | P5(MW) | P6(MW) |
|---|---|---|---|---|---|---|
| 1 | 5.0008 | 5.0008 | 5.0008 | 196.2107 | 162.8319 | 10.0007 |
| 2 | 5.0053 | 5.0053 | 5.0053 | 212.8319 | 136.3930 | 10.0045 |
| 3 | 5.0000 | 5.0000 | 5.0000 | 259.0458 | 100.0000 | 10.0000 |
| 4 | 5.0057 | 5.0057 | 5.0057 | 186.1608 | 162.8319 | 10.0048 |
| 5 | 5.0007 | 5.0007 | 5.0007 | 208.1709 | 162.8319 | 10.0006 |
| 6 | 5.0035 | 5.0035 | 5.0035 | 161.6760 | 162.8319 | 10.0009 |
| 7 | 5.0053 | 5.0053 | 5.0053 | 212.8319 | 136.3665 | 10.0045 |
| 8 | 5.0000 | 5.0000 | 5.0000 | 150.0000 | 186.9370 | 10.0000 |
| 9 | 5.0000 | 5.0000 | 5.0000 | 150.0000 | 186.9370 | 10.0000 |
| 10 | 14.3993 | 14.3990 | 14.3985 | 212.8319 | 225.6637 | 10.0076 |
| 11 | 5.0008 | 5.0008 | 5.0008 | 212.8319 | 280.1152 | 10.0007 |
| 12 | 15.4559 | 15.4559 | 15.4554 | 299.9994 | 162.8319 | 10.0016 |
| 13 | 8.9921 | 8.9918 | 9.2627 | 212.8319 | 288.4956 | 10.0060 |
| 14 | 5.0188 | 5.0191 | 5.0190 | 234.3860 | 288.4956 | 10.0115 |
| 15 | 12.2139 | 12.2027 | 12.1984 | 212.8320 | 288.4956 | 10.0074 |
| 16 | 12.2101 | 12.2868 | 12.1182 | 212.8319 | 288.4956 | 10.0075 |
| 17 | 19.8203 | 14.2861 | 23.2076 | 214.0026 | 288.4956 | 10.0078 |
| 18 | 16.0069 | 16.0120 | 29.5956 | 212.8319 | 288.4956 | 10.0081 |
| 19 | 5.0002 | 5.0002 | 14.5957 | 275.6637 | 281.4401 | 10.0001 |
| 20 | 13.2915 | 16.6802 | 13.7013 | 299.9967 | 288.4956 | 10.0058 |
| 21 | 17.0362 | 17.4008 | 16.0768 | 299.9971 | 288.4956 | 10.0082 |
| 22 | 29.9973 | 29.9973 | 29.9975 | 275.7002 | 288.4956 | 14.4138 |
| 23 | 17.3362 | 17.1813 | 16.1484 | 275.6639 | 288.4956 | 10.0078 |
| 24 | 29.4890 | 29.4890 | 29.4891 | 212.8319 | 288.4956 | 10.0081 |

## V. RESULTS

In this paper, particle swarm optimization (PSO) is used to optimize the cost function of wind-thermal generator units. It uses number of particles, looking for the best solution. Problems having noise, partial irregular, and change over time are optimized using PSO.

### *A. Solving by PSO*

Particle swarm optimization technique used in that case for obtaining the feasible solution with respect to the constrained. Table IV shows the result with valve point loading effects and ramp rate limits for cost function optimization using particle swarm optimization. The total cost is $203800.

### *B. Solving by Interior point*

Traditional technique used in that case for obtaining the feasible solution with respect to the equality and inequality constrained and reaches their feasible solution .In Table V shows the result with valve point loading effects and ramp rate limits for cost function optimization using interior point algorithm. The total cost is $207180.

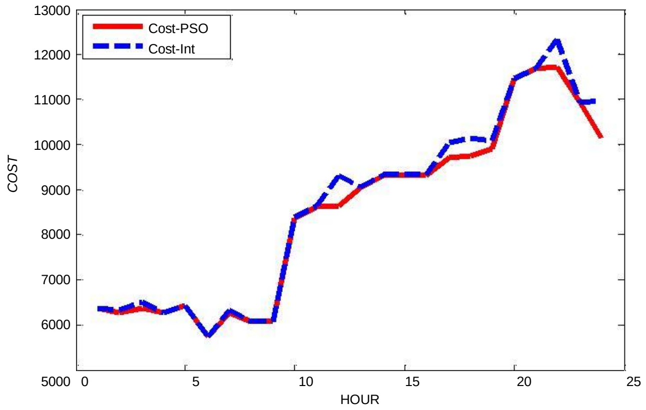

Fig. 5. Hourly distribution of cost by using PSO and interior point algorithm.

## VI. CONCLUSION

A short-term optimal operation dispatch of a power generation company with integrated wind and storage is studied in this paper. The wind- thermal dispatch problem is formulated and solved by using particle swarm optimization (PSO) algorithm and interior point algorithm. Analysis with valve point loading effects and ramp rate limits is given. According to the cases study results are shown that the PSO optimization technique reaches better feasible result as compare to the interior point algorithm. So the PSO optimization technique is little better than the interior point methodology. PSO is capable to solve non-linear and non-convex irregularities while interior point cannot work with non-linearity and non-convexity.

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