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Optimal Scheduling of Coordinated Wind-Pumped Storage-Thermal System Considering Environmental Emission Based on GA Based Heuristic Optimization Algorithm

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Abstract

The integration of renewable wind and pumped storage with thermal power generation allows for dispatch of wind energy by generation companies (GENCOs) interested in participation in energy and ancillary services markets. However, to realize the maximum economic profit, optimal coordination and accounting for reduction in cost for environmental emission is necessary. The goal of this study is to develop a simulation model for maximizing economic profit from coordination of renewable wind and pumped storage with thermal power generation for a GENCO with participation in energy and ancillary services markets with considerations for environmental emission and uncertainty associated with wind power based on a newly developed GA-based heuristic optimization algorithm. It is determined that for a GENCO with 13 MW wind farm capacity and 1662 MW thermal units, for meeting an average demand of 1129 MW, the utilization of 120 MW pumped storage in a coordinated wind-pumped storage-thermal system results in reduction of environmental emission by 13.54%, which leads to an increase in profit by 2.10%, as compared with operation with no pumped storage unit.

Keywords: Coordinated wind-pumped storage-thermal, energy and spinning reserve markets, environmntal emission, Genetic algorithm, wind uncertainty.
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1. Introduction

The integration of renewable wind and pumped storage units with thermal units is expected to lead to higher profit for a GENCO, when all associated costs for fuel and environmental emissions are accounted for. However, for maximizing economic profits, GENCOs with large portfolios of generators need to optimally coordinate power generation from wind, pumped storage, and thermal units. Accordingly, a coordinated wind-pumped storage-thermal scheduling problem is established and it must be optimized subject to all operation modes and market constraints [1-3].

The literature review shows that numerous studies have been conducted based on different combinations of generation resources and their potential benefits to be realized from coordinated and uncoordinated operations, as summarized in Table 2 and outlined as follows. For a GENCO with wind farm and pumped storage units, self-scheduling of coordinated operation with consideration for the uncertainty of wind power is examined by Karimi et al. [3], using general algebraic modeling system (GAMS) package software. Stochastic optimization of the daily operation of wind farm and pumped storage units are discussed by [4-6] without considerations for thermal units and environmental emission. The uncertainty of wind power is also modeled by Abarghooee et al. [7] for cost-based unit commitment for coordinated wind-thermal system with considerations for environmental emission, using modified teaching-learning algorithm. Wind farm and pumped storage units are coordinated with thermal units in generation scheduling problem using particle swarm optimization and GAMS by Siahkali [8, 9] without considerations for spinning reserve requirements and environmental emission constraints. Cost-based unit commitment problem for coordinated pumped storage and thermal units is solved by Nazari et al. [10, 11] for peak shaving and valley filling, providing spinning reserve, and reducing costs and environmental emission [10]. In some studies, environmental emission is considered in cost-based thermal unit commitment problem with considerations for pumped storage units [12, 13] and wind farm units [14-19], however, the potential economic profits to be realized from integrated operation and uncertainty of wind power are not addressed. Robust cost-based unit commitment of wind, pumped storage, and thermal units is presented by Jiang et al. [20] using benders decomposition algorithm. Cost-based unit commitment of wind, pumped storage, and thermal units is also presented by [21, 22] without considerations for environmental emission. Economic-emission unit commitment for coordinated wind-pumped storage-thermal system is examined by Verma et al. [23] however, the uncertainty of wind power and operation costs of wind-pumped storage system are not accounted for. Joint operation of wind farm, photovoltaic, and pumped storage and energy storage devices in energy and reserve markets is presented by Parastegari et al. [24] without considerations for thermal units and environmental emission. The coordinated operation of the wind farm and energy storage system is studied by Ding et al. [25].

2. Contributions

Based on literature review, it is hypothesized that, when renewable energy sources are integrated with non-renewable power generation systems, the induced effects of potential reduction in environmental emission on economics of operation is substantial. The goal of this study is to develop a simulation model for maximizing economic profit from coordination of renewable wind and pumped storage with thermal power generation for a GENCO with participation in energy and ancillary services markets with considerations for environmental emission and uncertainty associated with wind power based on a newly developed Genetic algorithm (GA)-based heuristic optimization algorithm. The remainder of this study is presented as follows. Section II introduces the problem formulation for scheduling of the wind-pumped storage-thermal system and, Section III explains the heuristic optimization algorithm developed for this study. Simulation results are discussed in Section IV, and finally, in Section V, conclusion remarks along with recommendations are given.

3. Problem Formulation

In this section, the problem formulation for scheduling wind farm and pumped storage with thermal units is given. It is noted that all variables and parameters are defined in Ref. [25].

A) *Uncoordinated wind-pumped storage-thermal system*

(a) Wind farm

The objective function for wind farm unit consists of revenues from energy bidding under various scenarios and costs

$$PF_W = R_1 + R_2 \tag{1}$$

$$R_1 = \sum_{t=1}^{T} MP_t^e \left(P(W,t) \right) \tag{2}$$

$$R_2 = \sum_{t=1}^{T} \sum_{m} p_m \Big[MP_t^{up} \left(P_W(m,t) - P(W,t) \right) \left(1 - b(m, \right. \\ \left. - MP_t^{down} \left(P(W,t) - P_W(m,t) \right) b(m,t) \Big] \tag{3}$$

where Eq. (2) represents the revenues of wind farm unit including the trading in energy market. The first term of Eq. (3) denotes that the wind farm unit is still paid for whatever excessive energy is produced beyond what is offered but at a different price (MP_t^{up}). The second term of Eq. (3) is a penalty of the wind farm unit if it does not produce as much as it offers. For the objective function of wind farm unit, the constraint is

$$0 \le P(W,t) \le P_{W-\max} \tag{4}$$

where Eq. (4) shows the constraint of wind farm unit capacity.

(b) Pumped storage unit

The pumped storage unit can participate in energy, spinning reserve, and regulation markets, simultaneously. The corresponding objective function is described by

$$PF_{PS} = R_1 + R_2 + R_3 + R_4 + R_5 - C_{o\&m} \tag{5}$$

$$R_1 = \sum_{t=1}^{T} \sum_{l=1}^{L} MP_t^e \left(P_g(l,t) - P_p(l,t) \right) \tag{6}$$

$$R_2 = \sum_{t=1}^{T} \sum_{l=1}^{L} MP_t^s \left(P_{p-SR}(l,t) + P_{g-SR}(l,t) \right) \tag{7}$$

$$R_3 = \sum_{t=1}^{T} \sum_{l=1}^{L} MP_t^r \left(P_{g-r}(l,t) \right) \tag{8}$$

$$R_4 = \sum_{t=1}^{T}\sum_{l=1}^{L} MP_t^{spot}\left(P_{p-SR}(l,t) + P_{g-SR}(l,t)\right) p_s \quad (9)$$

$$R_5 = \sum_{t=1}^{T}\sum_{l=1}^{L} MP_t^{spot} P_{g-r}(l,t)\left(p_r^{up} - p_r^{down}\right) \quad (10)$$

$$C_{o\&m} = \sum_{t=1}^{T}\sum_{l=1}^{L} K_1 + K_2\Big[\left(P_g(l,t) + P_p(l,t)\right) + \left(P_{g-SR}(l,t) - P_{p-SR}(l,t)\right) p_s + P_{g-r}(l,t)\left(p_r^{up} - p_r^{do}\right. \quad (11)$$

where Eqs. (6)-(8) represent the revenues of pumped storage unit including the trading in energy, spinning reserve, and regulation markets, respectively. Equations (9) and (10) express the income from pumped-storage unit from power delivery request of system operator in the spinning reserve and the regulation reserve markets, respectively. Operation and maintenance costs are considered by Eq. (11) including fixed and variable costs. The objective function of pumped storage unit given by Eq. (5) is subject to the following constraints

– Lower and upper limits of generation and pumping

$$0 \le P_g(l,t) \le P_{g-\max}(l) \quad (12)$$

$$0 \le P_p(l,t) \le P_{p-\max}(l) \quad (13)$$

$$0 \le P_{g-r}(l,t) \le P_{g-\max}(l)/2 \quad (14)$$

$$P_{g-r}(l,t) \le P_g(l,t) \quad (15)$$

$$0 \le P_{g-SR}(l,t) \le P_{g-\max}(l) \quad (16)$$

$$0 \le P_{p-SR}(l,t) \le P_p(l,t) \quad (17)$$

$$P_{g-r}(l,t) + P_g(l,t) + P_{g-SR}(l,t) \le P_{g-\max}(l) \quad (18)$$

For a pumped storage unit, it is impossible to have pumping and generation, simultaneously.

$$u_p(l,t) + u_g(l,t) \le 1 \quad (19)$$

Changeover time from pumping to generation and vice versa must be equal to or greater than one hour.

$$u_p(l,t) + u_g(l,t+1) \le 1 \quad (20)$$

$$u_g(l,t) + u_p(l,t+1) \le 1 \quad (21)$$

– Energy storage balance and limits for upper reservoir

$$E(l,t) = E(l,t-1) - P_g(l,t) + \eta P_p(l,t) - P_{g-r}(l,t)\left(p_r^{up} - p_r^{down}\right) - \left(\eta . P_{p-SR}(l,t) + P_{g-SR}(l,t)\right) p_s \quad (22)$$

$$E_{\min}(l,t) \le E(l,t) \le E_{\max}(l) \quad (23)$$

$$E(l,T) = E(l,0) \quad (24)$$

Minimum energy stored in upper reservoir

$$E_{\min}(l,t) = E_{\min}(l) + P_{g-r}(l,t+1) + P_{p-SR}(l,t+1) + P_{g-SR}(l,t+1) \quad (25)$$

(c) Thermal unit

The objective function of thermal units is to maximized the profit for GENCO defined as the revenue minus cost

$$PF_{Th} = R_1 + R_2 + R_3 - C_{o\&m} - C_{em} \quad (26)$$

$$R_1 = \sum_{t=1}^{T}\sum_{i=1}^{N} MP_t^e P(i,t) \quad (27)$$

$$R_2 = \sum_{t=1}^{T}\sum_{i=1}^{N} MP_t^s R(i,t) \quad (28)$$

$$R_3 = p_s . \sum_{t=1}^{T}\sum_{i=1}^{N} MP_t^{spot} R(i,t) \quad (29)$$

$$C_{o\&m} = FC + SC \quad (30)$$

where Eqs. (27) and (28) represent the revenues of thermal units including the trading in energy and spinning reserve markets, respectively. Equation (29) expresses the income from thermal units from power delivery request of system operator in the spinning reserve market. Operation and maintenance costs are considered by Eq. (30) based on fuel and start-up costs

$$FC = \sum_{t=1}^{T}\sum_{i=1}^{N} (1-p_s) f(P(i,t)) + p_s . f\left(P(i,t) + R(i,\right. \quad (31)$$

$$SC = \sum_{i=1}^{N}\left\{SUC(i,t) I(i,t)(1 - I(i,t-1))\right\} \quad (32)$$

where fuel cost is modeled with second-order generation cost function and start-up cost given by

$$f(P(i,t)) = a_i P^2(i,t) + b_i P(i,t) + c_i \quad (33)$$

$$SUC(i,t) = \begin{cases} HSC(i) & T^{OFF}(i,t) \le CST(i) + MDT(i) \\ CSC(i) & T^{OFF}(i,t) > CST(i) + MDT(i) \end{cases} \quad (34)$$

$$I(i,0) = IS(i) \quad (35)$$

The environmental emission cost for thermal unit is described as

$$C_{em} = EMP.\left(\alpha_i P^2(i,t) + \beta_i P(i,t) + \gamma_i\right) \quad (36)$$

The objective function for thermal units given by Eq. (26) is subject to the following constraints,

– Generation capacity

$$P_{\min}(i) I(i,t) \le P(i,t) \le P_{\max}(i) \quad (37)$$

– Minimum up/down time

$$T^{ON}(i,t) \geq MUT(i)$$
$$T^{OFF}(i,t) \geq MDT(i) \tag{38}$$

B) *Coordinated wind-pumped storage-thermal system*

The objective function of coordinated wind-pumped storage-thermal system consists of profits from energy, spinning reserve, and regulation markets.

$$PF_{WPST} = R_1 + R_2 + R_3 + R_4 + R_5 - C_{o\&m} - C_{em} \tag{39}$$

$$R_1 = \sum_{t=1}^{T} MP_t^e P_{WPST}(t) \tag{40}$$

$$R_2 = \sum_{t=1}^{T} MP_t^s R_{WPST}(t) \tag{41}$$

$$R_3 = MP_t^r \sum_{l=1}^{L} P_{g-r}(l,t) \tag{42}$$

$$R_4 = \sum_{t=1}^{T} MP_t^{spot} R_{WPST}(t) p_s + \sum_{t=1}^{T} \left\{ \sum_m p_m MP_t^{down} (1 - b(m,t)) \left(P(i,t) + \sum_{l=1}^{L} \left(P_g(l,t) - P_p(l,t) \right) + P_W(m,t) \right) - P_{WPST}(t) \right\} \tag{43}$$

$$R_5 = \sum_{t=1}^{T} MP_t^{spot} \sum_{l=1}^{L} P_{g-r}(l,t) \left(p_r^{up} - p_r^{down} \right) \tag{44}$$

C) *Wind uncertainty and spot prices modeling*

An artificial neural network is used to forecast the wind speed for calculation of wind power, as required for scheduling of wind farm unit in energy market. Modeling the wind power uncertainty and generation probabilistic production scenarios are detailed in Ref. [25]. To forecast the hourly spot market prices based on peak hours,

$$MP_t^{spot} = \begin{cases} (1+\gamma) MP_t^e & 0 \leq \gamma \leq 0.25 \quad 9 \leq t \leq 1 \\ (1+\mu) MP_t^e & -0.1 \leq \mu \leq 0.1 \quad \text{otherwis} \end{cases} \tag{45}$$

Positive and negative imbalance prices depend on the considered regulation mechanism. In this study, they simply equal to a certain proportion of MP_t^e.

$$MP_t^{up} = (1-\tau) MP_t^e \tag{46}$$

$$MP_t^{down} = (1+\tau) MP_t^e \tag{47}$$

4. Heuristic Optimization Algorithm

In this section, the heuristic optimization algorithm to solve scheduling problem is discussed. To show the pumped storage capability of reducing environmental emission from thermal units, the demand and spinning reserve constraints are

$$\sum_{l=1}^{L} \left(P_g(l,t) - P_p(l,t) \right) + P(W,t) + \sum_{i=1}^{N} P(i,t) = D(t) \tag{48}$$

$$\sum_{l=1}^{L} \left(P_{p-SR}(l,t) + P_{g-SR}(l,t) \right) + \sum_{i=1}^{N} R(i,t) = R(t) \tag{49}$$

To find optimal scheduling of coordinated wind-pumped storage-thermal system, the following procedure is used.

1. Optimal fitness functions (*FF*s) of wind, pumped storage, and thermal units are calculated as

$$FF^*(W,t) = RV_W(W,t) / \text{cost}_W(W,t) = f\left(P^*(W,t) \right) \tag{50}$$

$$FF^*(l,t) = RV_{PS}(l,t) / \text{cost}_{PS}(l,t) = f\left(P^*(l,t), R^*(l,t) \right) \tag{51}$$

$$FF^*(i,t) = RV(i,t) / \text{cost}(i,t) = f\left(P^*(i,t), R^*(i,t) \right) \tag{52}$$

where P^* and R^* are calculated using GA based on initial population=20, crossover rate of 80%, and convergence is reached when fitness function tolerance is lower than 10^{-6}.

2. Sort *FF*s. Starting from highest *FF*, units are committed until Eqs. (53) and (54) are satisfied.

$$\sum_{l=1}^{L} \left(P_g(l,t) - P_p(l,t) \right) + P(W,t) + \sum_{i=1}^{N} P(i,t) \geq D(t) \tag{53}$$

$$\sum_{l=1}^{L} \left(P_{p-SR}(l,t) + P_{g-SR}(l,t) \right) + \sum_{i=1}^{N} R(i,t) \geq R(t) \tag{54}$$

3. Economic dispatch is executed using *DCPR* and *ICPR* as discussed in [25] to find optimal output power of committed units to satisfy Eq. (48).

4. As constraints for *MUT* and *MDT* must be satisfied, some thermal units must be turned on or off. Accordingly, if start-up costs for a group of turned on thermal units are more than its profits, all thermal units of that group are turned off and vice versa.

5. Thermal units can provide pumping requirement if the cost of selling energy for required pumping is greater than the corresponding cost of thermal units. As noted earlier, pumped storage units can reduce the effects of uncertainty associated with wind power. If reducing the effects of uncertainty associated with wind power is profitable by participating in energy market, spinning reserve is used to compensate the difference between actual value of wind power (P_{Wt}) and power offered ($P(W,t)$). Also, if reducing the effects of uncertainty associated with wind power is not profitable, all of spinning reserve is sold in spinning reserve market.

6. Modification of output power and spinning reserve of thermal units when spinning reserve of

pumped storage compensates the difference between P_{Wt} and $P(W,t)$.

7. Total profit is calculated.

5. Simulation Results

The simulation results are presented to examine economic profit improvements and emission reductions achieved based on the heuristic optimization algorithm developed in this study. For data, a wind farm unit [25] with $P_{W-\max} = 13$ MW, a pumped storage unit with $P_{g-\max} = 12$ MW, and 10 thermal units with $P_{\max} = 1662$ MW [25] are used. All required data are available in Ref. [25]. In this case, GENCO is responsible to meet demand as well as spinning reserve (at 10% of demand) for 24-hr operation period, while environmental emission is considered and the associated costs are accounted for. To demonstrate the effects of pumped storage unit on profit and environmental emission, pumped storage unit is coordinated with wind-thermal system, identified as coordinated wind-pumped storage-thermal system. As discussed in section III, GA is used to find optimal P^* and R^*. For example, the GA convergence curves for thermal unit 2 at hr 12 are shown in Fig. 1. The results for optimal scheduling of coordinated hourly wind-thermal system with and without pumped storage unit with considerations for environmental emission are presented in Table 1.

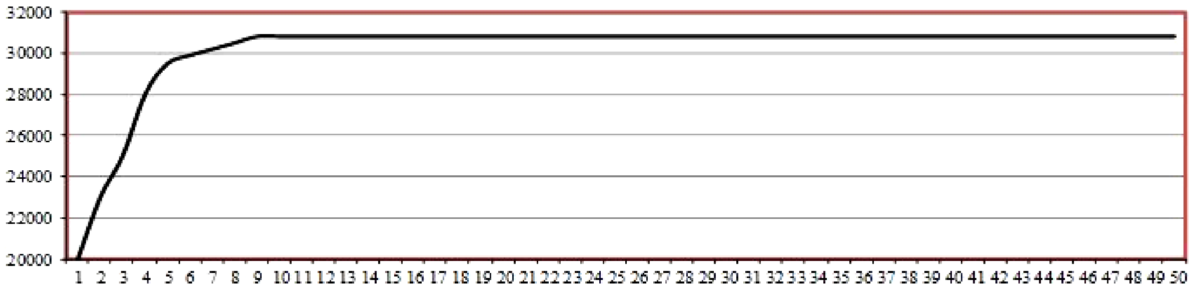

Fig. 1. The GA convergence curve for thermal unit 2 in hr 2

Table.1.
Simulation results for coordinated wind-pumped storage-thermal system with considerations for environmental emission

(a) Without pumped storage unit

Hour	Output power (MW)											Spinning reserve (MW)									
	Wind farm	Thermal units										Thermal units									
		1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
1	8	307	385	0	0	0	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0
2	8	356	380	0	0	0	0	0	0	0	0	0	75	0	0	0	0	0	0	0	0
3	9	341	370	0	130	0	0	0	0	0	0	0	85	0	0	0	0	0	0	0	0
4	7	323	360	130	130	0	0	0	0	0	0	0	95	0	0	0	0	0	0	0	0
5	10	375	355	130	130	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0
6	9	324	345	130	130	162	0	0	0	0	0	0	110	0	0	0	0	0	0	0	0
7	10	445	340	130	130	95	0	0	0	0	0	0	115	0	0	0	0	0	0	0	0
8	10	445	335	130	130	150	0	0	0	0	0	0	120	0	0	0	0	0	0	0	0
9	11	444	325	130	130	162	73	25	0	0	0	0	130	0	0	0	0	0	0	0	0
10	9	446	455	130	130	162	33	25	0	10	0	0	0	0	0	0	47	60	0	33	0
11	8	447	455	130	130	162	73	25	0	10	10	0	0	0	0	0	7	60	0	33	45
12	8	447	455	130	130	162	80	52	10	10	10	0	0	0	0	0	0	33	27	45	45
13	5	450	455	130	130	162	33	25	0	10	0	0	0	0	0	0	47	60	0	33	0
14	5	450	455	130	20	162	53	25	0	0	0	0	0	0	110	0	20	0	0	0	0
15	5	450	335	130	130	150	0	0	0	0	0	0	120	0	0	0	0	0	0	0	0
16	5	410	350	130	130	25	0	0	0	0	0	0	105	0	0	0	0	0	0	0	0
17	4	356	355	130	130	25	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0
18	5	328	345	130	130	162	0	0	0	0	0	0	110	0	0	0	0	0	0	0	0
19	4	451	335	130	130	150	0	0	0	0	0	0	120	0	0	0	0	0	0	0	0
20	6	449	455	130	130	162	33	25	0	10	0	0	0	0	0	0	47	60	0	33	0
21	8	447	455	130	53	162	20	25	0	0	0	0	0	0	77	0	53	0	0	0	0
22	5	328	455	130	0	137	20	25	0	0	0	110	0	0	0	0	0	0	0	0	0
23	6	309	455	130	0	0	0	0	0	0	0	90	0	0	0	0	0	0	0	0	0
24	9	336	455	0	0	0	0	0	0	0	0	80	0	0	0	0	0	0	0	0	0

(b) With pumped storage unit

Hour	Output power (MW)											Spinning reserve (MW)									
	Wind farm	Thermal units										Thermal units									
		1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
1	8	150	282	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	8	150	332	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	9	150	431	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	7	323	455	130	35	0	0	0	0	0	0	0	0	0	95	0	0	0	0	0	0
5	10	375	455	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	9	420	455	130	130	25	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0
7	10	455	455	130	20	80	0	0	0	0	0	0	0	0	110	5	0	0	0	0	0
8	13	450	455	130	130	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	13	455	455	130	130	119	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
10	9	455	455	130	130	162	59	0	0	0	0	0	0	0	0	0	20	0	0	0	0
11	13	455	455	130	130	162	80	30	0	0	0	0	0	0	0	0	0	25	0	0	0
12	8	455	455	130	130	132	80	80	0	30	0	0	0	0	0	30	0	0	0	0	0
13	5	455	455	130	130	162	38	25	0	0	0	0	0	0	0	0	20	0	0	0	0
14	13	455	455	130	130	125	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
15	5	455	455	130	130	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	5	305	455	130	130	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	4	256	455	130	130	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	5	355	455	130	130	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	4	455	455	130	130	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	6	455	455	130	130	142	0	0	0	55	27	0	0	0	0	20	0	0	0	0	0
21	8	455	455	130	130	122	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
22	5	380	455	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	6	179	455	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	9	150	381	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table.2.
Simulation results for coordinated wind-pumped storage-thermal system considering environmental emission

	Profit ($)				Profit Improvement (%)	Emission (TOC)	Emission reduction (%)
	Wind farm	Pumped storage	Thermal	Total			
Without pumped storage	6,551.00	0.00	563,139.00	569,690.00	-	4,300.0	-
With pumped storage	6,621.00	44,869.05	530,140.00	581,630.05	2.10	3,717.6	13.54

As shown in Table 2, it is determined that the utilization of pumped storage reduces emission from thermal units by 13.54% resulting in profit increase of 2.10%. Also, as providing spinning reserve is less profitable than reducing the effects of uncertainty associated with wind power, the profit of wind farm unit is changed with pumped storage. Also, in coordinated operation, almost all of spinning reserve requirement is met by pumped storage unit as presented in Fig. 2. It is observed from Fig. 3 that in coordinated operation, emission from thermal units is decreased for nearly all hours of operation, whereas nearly all the spinning reserve requirement is almost met by pumped storage unit. Further, energy storage and required minimum energy in the upper reservoir of coordinated pumped storage unit is depicted in Fig. 4.

6. Conclusions and recommendations

In this study, a simulation model for evaluating the economic profit from integration of renewable wind and pumped storage with thermal power generation for a GENCO participating in energy and ancillary services markets is developed for the purposes of analyzing the effects of considerations for environmental emission that must be addressed in renewable energy utilization. The developed heuristic optimization algorithm is used for optimal coordination of generation units and, with considerations for environmental emission, for a GENCO with wind farm and thermal units, it is shown that utilization of pumped storage decreases emission by 13.54% which leads to an increase in profit by 2.10%, as compared with operation with no pumped storage unit.

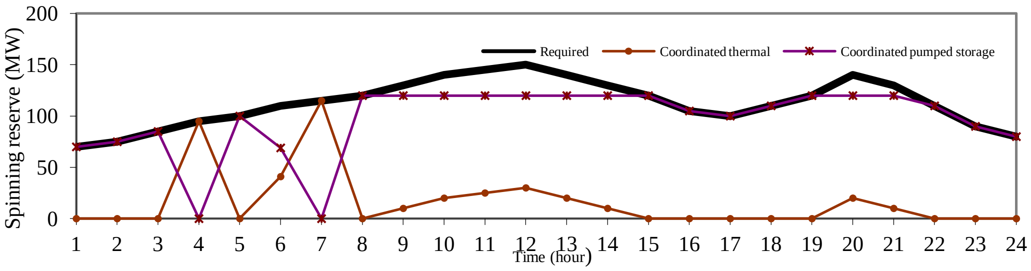

Fig. 2. Spinning reserve met by coordinated pumped storage and thermal units.

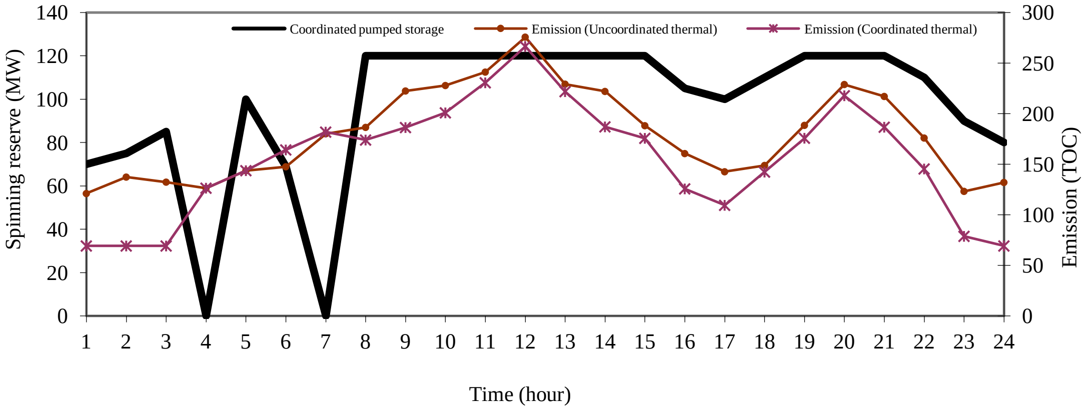

Fig. 3. Spinning reserve met by coordinated pumped storage unit and emission from thermal units.

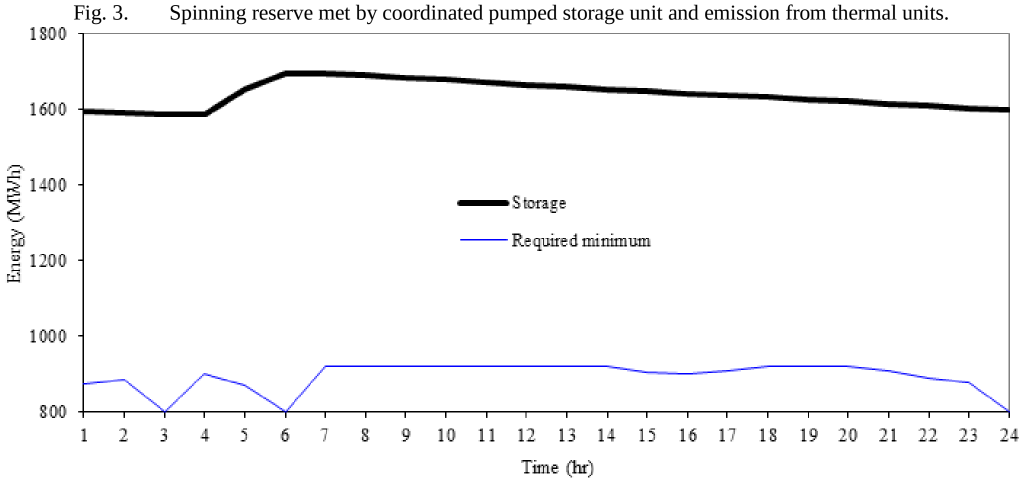

Fig. 4. Pumped storage energy storage in upper reservoir and required minimum energy.

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