Dynamic Self-Scheduling of Pumped-Storage Power Plant in Energy and Ancillary Service Markets Using Sliding Window Technique

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Abstract—In the competitive electricity market environment, the profit of the pumped-storage plant in the energy market can be maximized by operating it as a generator, when market clearing price is high and as a pump, to pump water from lower reservoir to upper reservoir, when the price is low. An optimal self-scheduling plan has been developed for a pumped-storage plant, carried out on weekly basis in order to maximize the profit of the plant, keeping into account of all the major uncertainties such as the sudden ancillary service delivery request and the price forecasting errors. For a pumped storage power plant to operate in a real time market successive self scheduling has to be done by considering the forecast of the day-ahead market and the modified reservoir storage due to the ancillary service request of the previous day. Sliding Window Technique has been used for successive self scheduling to ensure profit for the plant.

Keywords—Ancillary services, BPSO, Power System Economics (Electricity markets), Self-Scheduling, Sliding Window Technique.

I. INTRODUCTION

PUMPED-STORAGE hydro electric power plant is in operation since the 80's and because of its swift response to the change in load demand and market price, it is still in high demand. It can be called as an energy storage device where water is being recycled between upper and lower elevation reservoirs, when demand is low and high, respectively. A pumped-storage plant owner can buy or sell energy in the day-ahead markets or with bilateral contracts [1]. Pumped-storage is ideally suited where there is a significant difference in power demand between on-peak and off-peak periods as well in the cost of producing energy in these periods.

Real time market is a balancing market which is used to match the real time generation and demand during normal operating conditions. Another kind of market is the ancillary service market, which delivers the voltage regulation support, reactive power support and other spinning and non-spinning reserves. Trading in these markets, lead to the profit maximization for a pumped-storage plant. As the market prices of the energy and ancillary services are interrelated, the plant has the choice of market that return the highest profit. By

optimizing the self-scheduling plan of the plant according to the varying load demand helps the plant to get strong incentives in the multi service markets. Some of the early works in which self-scheduling had been performed based on the spot market forecasted prices, and by ignoring any of the uncertainties, which may be observed in the electricity markets have been explained.

Recently, many articles have been published for self-scheduling of price-taker generators, however, about the self-scheduling of an energy storage device, is rare. In [4], an optimal bidding strategy for a pumped-storage plant in a competitive electricity market has been developed. Here the power which is being generated was not affected by the reservoir head and was assumed to be fixed. It was checked as a corrective criterion. The result of self-scheduling is valid until violation instance and then it is re-iterated for the remaining time. But by doing so, the total profit will decrease with the separation of time periods because intermediate optimization solutions are infeasible.

The papers [2]-[4] are the early works done on price-taker producers. An optimal bidding strategy, only considering the general technical constraints of the power plant are considered in [2] other constraints such as fuel and/or emission constraints are ignored. In [3] the variances of estimated energy, spinning reserves and regulation price revenues are determined according to the relevant historical data. These variances are adopted as risk criterion. Here a precise modeling of risk is embedded in the maximum profit problem being formulated, using Mixed Integer quadratic programming. A method to build bidding strategies for both suppliers and large consumers in Pool-Co market is proposed in [4] by assuming each supplier bids a linear supply function and system is dispatched to maximize social welfare. The problem is formulated as a stochastic optimization problem and is solved by Monte Carlo approach.

A stochastic optimization technique namely Particle Swarm Optimization (PSO) has gained much importance because of its accurate results for large period of optimization and its flexibility in dealing with non-linear plant models. But PSO may not effectively deal with the discrete nature of the pumped storage self-scheduling problem; therefore, Binary Particle Swarm optimization (BPSO) technique is adopted. The real-time market disturbances and the ancillary services request which leads to the uncertainty in commitment of the pumped-storage plant has been identified and the uncertain

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market environment is addressed using dynamic self-scheduling called Sliding Window Technique.

II. OPERATING CONSTRAINTS

Water is pumped to upper reservoir whenever the market prices are low, and the stored water is used for generation purpose when the price of power in the market is high. For this purpose, Francis turbine (reversible turbine-pump) along with synchronous machine is used.

The pumping power required will be more than the power required for generating with the same amount of water, because of plant losses. Therefore, if the plant efficiency is n ($0<n<1$) the unit will be able to generate energy of only n (in MWh) after consuming energy of 1MWh for the purpose of pumping water into upper reservoir [5]. Hence if the plant owner selects a bid for buying energy of 1MWh, and bid for the selling price of n (in MWh) for a time period of t_g (hr) such that the plant cycle efficiency of the unit is greater than the ratio of market clearing price's of pumping and generating respectively, the net plant profit will be maximized.

A. Economic Constraints

In a restructured electricity market, a MCP curve on daily and weekly basis can be plotted and by arranging the MCP's in ascending order, the composite plot is obtained [6]. The peak hours are from 5:00pm to 9:00pm and the valley hours are between 0:00am to 6:00am. Hence it can be concluded that the daily operating cycle of the plant will be pumping mode coming first and then the generating mode.

Let B_p be the maximum MCP (Rs/MWh) that the plant will have to pay for the energy from the electricity market and uses the energy to pump water from the lower reservoir to upper reservoir for storage purpose. Similarly let B_g (Rs/MWh) be the minimum price which the plant gets for selling electricity into the market.

The condition to be satisfied for the plant to be economically profitable is given by

$$Bg \geq \frac{Bp}{\eta p} \qquad (1)$$

The plant cycle efficiency n is typically 67% [7] therefore,

$$Bg \geq 1.5Bp \qquad (2)$$

B. Power Generation

This constraint of the plant strongly affects the strategy that is used for bidding in the electricity market. When the plant schedules in the peak hours, it should generate maximum possible generation from the available reservoir. Main characteristics of the pumped-storage plant are the power generating limits of the plant which is a strong function of head and technical constraints like discrete loads and generating schedules.

- Equivalent Energy and Power

The relation existing between the Energy stored and head is given by

$$Pl(i) = h(i) \times f(i) \times 5.9 \qquad (3)$$

$$El(i) = m \times g \times h(i) \times 2.78 \times 10^{-4} \qquad (4)$$

The relationship between the head of the reservoir, energy stored and flow rate gives the optimal power that the plant can produce.

The condition which should be maintained while optimizing is that the energy stored before the starting the scheduling should be equal to the amount of energy left once the scheduling is complete.

III. SELF-SCHEDULING STRATEGY FOR THE PLANT

The pumped-storage plant undergoes self-scheduling so as to attain maximum net profit. The net revenue achieved by the plant includes trading in the energy market and also by being accepted in the non-synchronous reserve market when the plant is in offline mode. The plant can also be committed for synchronous reserve market when it is pumping mode because it can readily serve to reduce its pumping mode, and consequently, reduce the overall system load.

A. Modeling of Plant Operation

A deregulated electricity market is considered, in which uniform pricing, which is equal to the Last Accepted Offer (LAO) scheme is followed for the computation of nodal prices (Power Exchange of India, available online). For a given hour, if the unit supplies the power of P_g (MW) at the price of B_{eg} (Rs/MWh) in the generating mode, then it receives $P_g \times B_{eg}$ (Rs). Similarly, if the unit consumes the power of P_p (MW) at the price of B_{ep} (Rs/MWh) in the pumping mode, then it pays $P_p \times B_{ep}$ (Rs). The net revenue expected to be received from day-ahead market by selling energy during generating mode for a period of t_g (h) and buying energy needed to pump water into the upper reservoir for a period of t_p (h) is

$$\sum_{i=1}^{tg} P_g(i)B_{eg}(i) - \sum_{j=1}^{tp} P_p(j) - B_{ep}(j) \qquad (5)$$

If the unit operates in pumping mode consuming a power of P_p (MW), and able to reduce the power consumed for pumping from P_p to $(P_p - P_{rs})$ (MW) during the reserve requirement, it can get paid for $P_{rs} \times B_{rs}$ (Rs), where, $0 \leq P_{rs} \leq P_p$ and B_{rs} (Rs/MWh) is the spinning reserve price. Revenue expected to be received from synchronous reserve market for the period of t_p (h) is

$$\sum_{k=1}^{t_p} P_{rs}(k)B_{rs}(k) \qquad (6)$$

When the unit is off-line, it can be committed as a non-synchronous reserve and get paid at $P_g \times B_{rn}$ (Rs), where B_{rn} (Rs/MWh) is the non-synchronous reserve price. Revenue expected to be received from non-synchronous reserve market by being accepted as a reserve for a period of $(T - t_p - t_g)$ (h) is

$$\sum_{m=1}^{T-t_p-t_g} P_g(m)B_{rn}(m) \qquad (7)$$

Considering fixed cost including maintenance expenditure of C_m (Rs) per T hours, the profit over the period of T (h) can be represented in the following equation:

$$P = \sum_{i=1}^{t_g} P_g(i)B_{eg}(i) - \sum_{j=1}^{t_p} P_p(j) - B_{ep}(j) + \sum_{k=1}^{t_p} P_{rs}(k)B_{rs}(k) + \sum_{m=1}^{T-t_p-t_g} P_g(m)B_{rn}(m) - C_m \qquad (8)$$

In order to maximize the profit, the plant owner should self-schedule the pumped-storage power plant for an optimal duration of pumping and generating during a cycle of T hours.

The storage plant generation constraints require that generation should be in between the low and high limit curves with respect to head h, respectively. In addition, the high limit constraint for the unit gets violated if plant continues its generation at the same level for the entire hour due to the decrease in head. Therefore the optimal power that can be generated should be found out using the iterative algorithm given in Section II *B*.

IV. SOLUTION USING BPSO

A. PSO basics

Particle swarm optimization (PSO) is an evolutionary computational technique that optimizes a problem by iteratively trying to improve a particle solution with regard to a given measure of quality. Each particle's movement is influenced by its local best known position called as *pbest* and is also guided toward the best known positions in the search-space, i.e. the *gbest* which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions.

B. BPSO

In the binary PSO, the best position of the particle and global best is updated as in real-valued form. The major difference between binary PSO with real-valued version is that velocities of the particles are rather defined in terms of probabilities that a bit will change to zero or one. Using this definition a velocity must be restricted within the range [0,1]. So a map is introduced to map all real valued numbers of velocity to the range [0,1]. The normalization function used here is a sigmoid function as:

$$S(v_{pd}^{k+1}) = \frac{1}{1 + \exp^{(-v_{pd}^{k+1})}} \qquad (9)$$

The new position of each bit d in the particle p is obtained using the equation below:

$$x_{pd}^{k+1} = \begin{cases} 1, if Rand(0,1) < S(v_{pd}^{k+1}) \\ 0, otherwise \end{cases} \qquad (10)$$

C. Binary Coding of Particle String

The limiting variables that optimize the objective function are the plant's operating mode and the power output/input. The plant operating mode is '1' for generating period and '0' for pumping period. If all the units are non-working, i.e. all bits are '0' then the plant is in off-line state. The particle structure should therefore be modified so that it can handle and make decisions on the two possible states. Since the pumping loads and generating schedules are discrete and they are handled on hourly basics, instead of plant's water discharge rate, the plant's generation output/power input is used as another control variable. Water dynamics and storage reservoir constraints are handled in terms of energy (MWh). The binary PSO considers the control variables as a particle string containing a mode bit followed by control variable of each unit. Here the particle string for 24 hrs of operation of a plant containing 24 substrings is briefed below.

1 0 0 0 1 1	0 0 1 0 1 1	....	1 0 0 0 1 1
Hour 1	Hour 2	.... Hour 24	

Fig. 1 Particle string for a pumped-storage plant with five units

Consider a pumped storage plant with five units. Fig. 1 represents a particle string that translates the encoded parameter of each plant into their binary representation, for e.g. say 24 hrs of operation.

The first block in each substring represents the mode of operation of the plant, i.e., whether the plant is generating, pumping or off-line. The remaining N blocks in the substring are used to represent respective power bids in the corresponding operating mode ranging between their respective maximum and minimum limits. When the plant is in off-line, corresponding power represents the non-synchronous reserve bid of the unit.

D. Algorithm for BPSO

1) Read the data and plant constraints.
2) Initialize the swarm keeping into account of the stored energy and available reservoir limits.
3) If the first bit of the substring is 1, i.e. the generating mode, calculate the optimal power that can be generated by the plant corresponding to the energy stored of the previous block.
4) Calculate the net energy available after the complete hour of generation

5) Now, if the first bit is 0, i.e. the pumping mode, then constant pumping power is taken from the grid. Also the plant cycle efficiency is considered to determine the pumping power required for pumping water into upper reservoir.
6) But if the energy balance condition is violated in either of the cases (pumping or generating), the plant remains in idle mode, and participates in non-synchronous reserves.
7) Estimate the profit of each string
8) Initialize the pbest as the current position of each string.
9) Initialize gbest as the best among all the pbest.
10) Update the position of the particle string.
11) Update the profit of the new particle string
12) Similarly update pbest and gbest if the new values are better than the previous pbest and gbest respectively.
13) Mutation is performed if gbest remains unchanged within 10 iterations.
14) Print gbest as the optimal solution
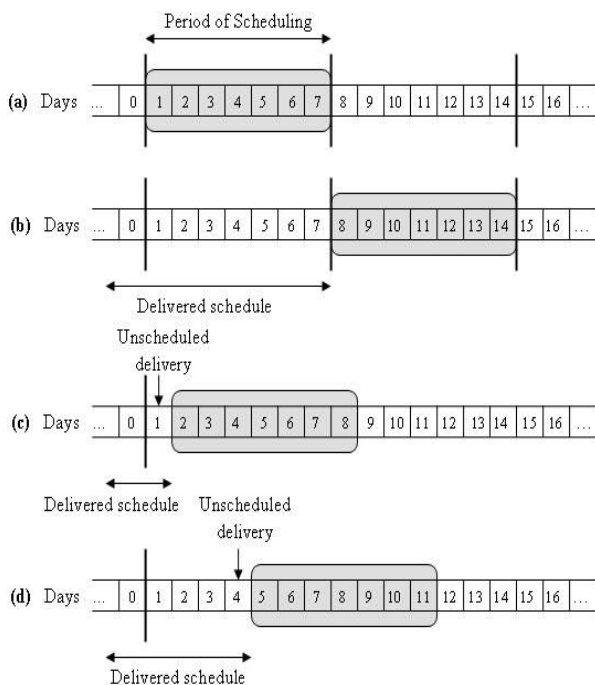Continue the process for required number of iterations.

Fig. 2 Self-scheduling during uncertain power delivery request

V. SLIDING WINDOW TECHNIQUE

The uncertainty in power delivery request from the ancillary services market makes the amount of energy stored in the upper reservoir uncertain, concerning to the already prepared self-scheduling strategy. Fig 2 depicts the sliding window technique, when the operation of the plant in the first day of the week is completed, the weekly schedule is executed for the subsequent six days only if the already prepared self-schedule is disturbed. If the period of scheduling is delivered without any disturbance, the window spans to next period of seven days. But if the schedule is disturbed in day 1 due to committed ancillary service power delivery request, then the self-schedule is repeated for the period starting from day 2 to day 8 and so on.

VI. SIMULATION RESULTS

The simulations were conducted in MATLAB environment. The optimal bidding strategy for self-scheduling of pumped-storage hydropower plant was coded in MATLAB and the results obtained are discussed below:

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Day																								
Monday	P	G	P	G	G	P	P	P	P	P	G	P	P	G	G	P	P	G	G	P	G	P	P	G
Tuesday	P	P	G	P	G	G	G	P	P	P	P	G	G	G	P	G	P	P	G	G	G	G	P	P
Wednesday	P	G	P	G	P	P	P	P	P	G	P	G	P	P	P	P	P	P	G	G	P	G	G	G
Thursday	G	P	P	P	G	G	G	G	P	G	I	P	G	P	P	P	P	G	P	P	P	P	G	P
Friday	P	P	P	G	P	G	G	G	P	G	G	G	G	I	I	P	G	P	G	I	I	P	I	I
Saturday	I	I	P	P	G	G	I	P	P	G	G	P	G	I	I	I	I	P	P	P	G	P	P	P
Sunday	P	P	G	P	P	G	P	P	G	G	G	G	P	P	G	G	P	G	P	P	P	P	G	G

Fig. 3 Optimal bidding strategy and corresponding schedule using BPSO methodology for weekly basis from june 15 to 21, 2013

Fig. 3 shows the schedule obtained by using BPSO method for a pumped storage plant for a week. Here, P, G, and I corresponds to pumping, generation and idle modes respectively.

A. Binary PSO Results

In the developed BPSO approach, the particle strings were iterated for 150 times, and population size of 50 was selected. The convergence characteristics of gbest and the results obtained is shown in Fig 4. The gbest converges to $1.5957×10^7$ Rs/MWh within 21 iterations.

TABLE I
PERFORMANCE OF THE BPSO METHOD

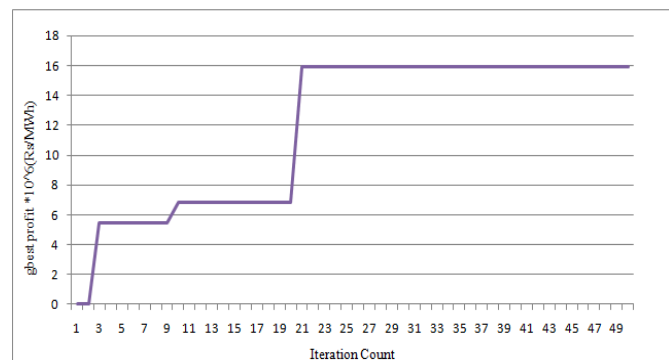| Parameters	Obtained value
Pumping time tp (h)	93
Generating time tg (h)	62
Average Power (MW)	67
Expected profit (Rs.)	1,59,57,000
Stored Energy (MWh)	2052.7

Fig. 4 Convergence characteristics of BPSO

The results of the pumped storage plant self-scheduling obtained by using BPSO are shown in the Table I.

B. Sliding Window Technique

The plant undergoes dynamic self-scheduling at the instant any disturbance occurs.

Fig. 5 (a) shows the case when a sudden power delivery request occurred at hour 36 in the grid. From Fig. 5 (a), it is clear that the plant has updated its data and has made a new scheduling plan from the next day to the following consecutive seven days. Similarly at 61st hour, the grid has extra power due to any sudden decrease in load leading to the plant to pump more and consequently reschedule its already made plan.

Fig. 5 (b) shows the plot when an error in forecasted price occurred in the 198th hour. This occurs when the power bid is not being accepted in the electricity market. During this hour the plant remains in idle mode.
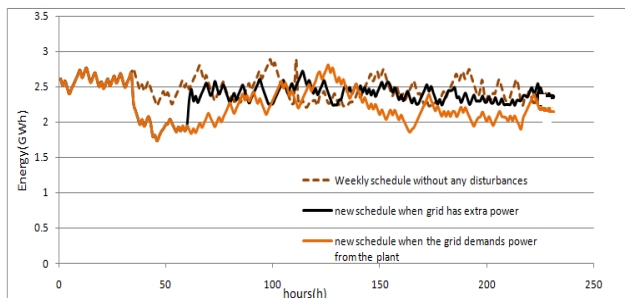
(a)
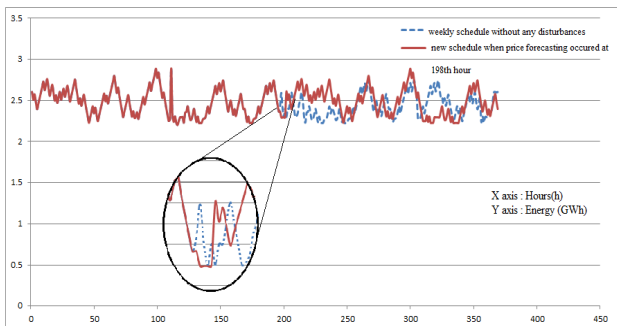
(b)

Fig. 5 Graphical representation of the plant performance for various disturbances (a) during ancillary service request and (b) during price forecasting error

The profit obtained by the pumped-storage power plant for different disturbance conditions is shown in the Table II. During disturbance in the price forecasting, the plant remains in the offline mode for that particular hour.

TABLE II
PROFIT OF THE PLANT FOR DIFFERENT OPERATING CONDITIONS

Different Cases	Profit (Rs/MWh)
Without any disturbance	1.5957×10^7
Power delivery request from grid during peak time (plant operating as a supplier)	1.8348×10^7
Excess power in the grid during off peak time (plant operating as a buyer)	1.6213×10^7
Disturbance in price forecasting	1.5601×10^7

VII. CONCLUSION

The self scheduling problem for a pumped storage power plant considering the plant uncertainties such as the plant reservoir capacity and market clearing price was done using BPSO. The successive self scheduling for a pumped storage power plant operating in a real time market with uncertainties of modified reservoir storage due to the ancillary service request of the previous day and the forecast of the day-ahead market has been done using Sliding Window Technique.

The simulation results clearly indicates the effectiveness of the Sliding Window Technique in optimizing the successive self-scheduling problem and it can also be seen from the results that the technique ensures profit to the plant participating in the real time market.

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