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Optimum scheduling of micro grid connected wind-pumped storage hydro plant in a frequency based pricing environment

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ABSTRACT

This paper presents a new formulation to maximize the operational profit of a micro grid connected hybrid system having wind farm and pumped storage unit for a day ahead electricity market in a frequency based pricing environment. Under frequency based pricing mechanism in India, the pricing for energy exchange is adaptive as per Availability Based Tariff (ABT) rate structure and the payment for deviation from schedule, i.e. Unscheduled Interchange (UI) charge is inversely proportional to the prevailing grid frequency. In this work, a small power system is considered as micro grid and it is expected that the hybrid system connected with the micro grid has a role to play to maintain the micro grid frequency. The pump storage hydro plant is operated to serve the dual role of minimizing the UI flow and maximizing the system economy by participating in frequency control based on energy price. The uncertainties in wind power prediction and loads are considered. The optimum operating schedule of PSH unit in coordination with wind farm is investigated. The optimization is performed by utilizing the water storage availability of pump storage hydro unit. An optimization algorithm is proposed and solved using Artificial Bee Colony algorithm. The solution of the proposed approach gives the strategies to be followed by the hybrid system to operate its pump storage unit. The effect of the initial storage water volume on the performance of the hybrid system has also been investigated. It reveals that the PSH units would not operate simply to compensate for the short fall or the surplus generation of the wind units in a frequency based pricing system. Rather, the pump storage units should take the advantage of the low price periods to maximize the profit of the hybrid system. The hourly energy management scenarios of the hybrid system with the micro grid are reported and the numerical case studies on PSH plant scheduling demonstrate the effectiveness of the proposed approach.

1. Introduction

With the increase in environmental awareness and strict regulation on environmental concerns, the clean, cheap energy generation and its utilization has attracted more attention than before over the last few years. There is continuous growth in the use of various types of Renewable Energy Sources (RES) in many countries around the world. The basic aim is to reduce the green house gas emissions caused by the conventional electric generators. To meet the emission cut target, attempts have been made to maximize the penetration of RES into electricity grids [1–3]. Wind power is the most widely used and acceptable source of renewable energy. The power generation largely depend on wind speed. Therefore, there are uncertainty and volatility associated with wind power generation.

To compensate for the uncertainty of wind generation system the uses of pumped storage hydro unit or battery storage in coordination with wind farm have been reported in the literature. The use of Pumped Storage Hydro (PSH) unit in coordination with wind farm has become an attractive solution. A number of research reports [4–6] analyze the operation of PSH unit to compensate the energy imbalance of smaller grid. The smaller grids with wind farm, face the difficulties to exploit fully the potentiality of wind power, mainly because of stochastic nature of wind and its seasonal variations. The PSH unit can play a significant role to recover the excess wind energy in the form of stored hydraulic energy during high wind periods and can participate in supplying energy to the grid during low wind periods by transforming the stored hydraulic energy into electricity. The basic optimization model for pumped storage hydro plant operation and coordinated operation of wind farm together with PSH unit has been discussed in [7,8] respectively. The problem has been

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Nomenclature

B_{ij}	line susceptance between bus i and j
c^t	hourly market price for schedule interchange in Rs/MW h
C_{PS}^t	cost of extra power sold to the micro grid in Rupees
C_{PPL}^t	cost of extra power purchased from micro grid for supplying load in Rupees
C_{PPP}^t	cost of power purchased from micro grid for pumping in Rupees
C_{SI}^t	cost of schedule interchange in Rupees
D_{LU}^t	uncertainty in load demand at hour t
$D_{LU}^{\max}$	maximum load demand uncertainty
E^t	hourly reservoir energy level in MW h
E^U	maximum energy level of the reservoir in MW h
E^L	minimum reservoir energy level to maintain in MW h
f^t	frequency at hour t in Hz.
G_{ij}	line conductance between bus i and j
i, j	index of buses
P_{HS}^t	hourly active power delivered by hybrid system to the micro grid in MW
P_W^t	hourly available wind power generation in MW
P_H^t	hydro generation from pumped storage hydro unit in MW
P_{CG}^t	hourly real power from central generators in MW
$P_{CG}^{\min}$	minimum real power of central generators in MW
$P_{CG}^{\max}$	maximum real power of central generators in MW
P_P^t	power consumption during pumping hours in MW
P_D^t	hourly real power demand in MW
P_H^L	minimum hydro generation in MW
P_H^U	maximum hydro generation in MW
P_P^L	minimum pump load in MW
P_P^U	maximum pump load in MW
P_{WU}^t	uncertainty in wind power at hour t
$P_{WU}^{\max}$	maximum wind power uncertainty
Q_{CG}^t	hourly reactive power generation from central generators in MVAR
Q_D^t	hourly reactive power demand in MVAR
Q_{HS}^t	hourly reactive power (if any) from hybrid system in MVAR
$Rate^{UI}$	rate of unscheduled interchange in Rs./MW h
S_{ij}^t	line flow between bus i and bus j in MVA at hour t
S_{ij}^U	maximum line loading limit of line between bus i and bus j in MVA
t	index of interval or hour
UI_{PS}^t	hourly extra power sold to the grid as unscheduled interchange in MW
UI_{PPL}^t	hourly extra power purchased from grid for load balance in MW
UI_{PPP}^t	hourly extra power purchased from grid for pumping in MW
UI^t	hourly unscheduled interchange in MW
UI^U	maximum unscheduled interchange
$\lvert V_i^t \rvert$	voltage magnitude at ith bus at hour t
$\lvert V_i^{\min} \rvert$	minimum voltage magnitude of bus i
$\lvert V_i^{\max} \rvert$	maximum voltage magnitude of bus i
η_H	efficiency of PSH unit during hydro generation
η_P	efficiency of PSH unit during pumping
θ_i, θ_j	voltage phase angle of ith bus and bus j

formulated as an Optimal Power Flow (OPF) which finds the working strategies of an Independent Power Producer (IPP) to minimize their operating cost. The improvement of operational economics of a wind farm for daily basis has been discussed in [9] by optimal utilization of its pumped storage hydro plant. The problem has been formulated as hourly discretized optimization problem for finding a daily operating strategy of both wind farm and pump storage plant. In this type of profit maximization problem, it is intended by the utility to operate its PSH unit to store water during low pricing periods or during high wind speed hours and to operate its PSH unit to discharge water during high pricing period or during inadequate wind speed hours. A hybrid practical power system consisting of wind farm with pumped storage hydro plant has been demonstrated in [10] and the suitability of its operating strategy has been discussed. A formulation has been made to improve the energy dispatch share from renewable energy sources by proper utilization of PSH unit. A joint optimization model under market environment has been addressed in [11] for both wind farm and PSH unit in two different mode of operation. The profit maximization is analyzed first by operating wind farm and PSH unit independently to exchange energy with the market and second, by operating the PSH unit in coordination with the wind farm. In Ref. [12], an optimum daily operational strategy has been discussed for an IPP having wind farm and PSH unit for a day ahead electricity market. The formulation has been tested on an Indian test system.

An accurate wind power prediction is necessary by the utility for finding such operational strategy. Inaccuracy in prediction has an impact on various issues of power system operation, such as; day ahead scheduling, optimal power flows, system stabilities, transmission congestions, and operational economics. The impact on market price due to inaccuracy in wind power prediction has been addressed in [13] when a large scale wind farm is integrated into an electric power system. The operating strategy of a wind power producer in a short term electricity market under uncertainty has been investigated in [14].

Power system restructuring and deregulation has changed the power system operation in respect to frequency regulation, generation redispatch, etc. The frequency regulation is the mechanism of controlling frequency by minimizing supply demand gap. Because of random variations in wind power generation, frequency fluctuation in grid has become a major concern in recent times. For random wind power penetration into the grid, the system stabilizes to a new steady operating point with a frequency different than the nominal. This frequency deviation from nominal would result unscheduled power flow through the lines if no control action is initiated. This Unscheduled Interchange (UI) flow would thus try to improve the grid prevailing frequency. The cost of UI flow is made frequency dependent in Indian power system operation [15]. The power system operations in Indian context under frequency based pricing have been reported in the literatures [16–18]. The Generation Scheduling (GS) problem as a day ahead activity has become an adaptive decision making problem under frequency based pricing [16]. GS strategy with the presence of pumped storage unit in a frequency based pricing environment [17] showed that a PSH unit can play important role in improving micro grid discipline by reducing overdraw under high UI charge. The PSH unit should have sufficient capacity to maintain frequency within allowable range. A day ahead unit commitment problem has been modeled and analyzed under frequency based pricing mechanism in [18]. The problem has been formulated as a mixed integer linear programming problem and tested on an Indian test system with the presence of PSH unit. The issues of frequency regulation under reformed system structure have been discussed in [19].

This paper focuses on profit maximization of a micro grid connected hybrid system under frequency based pricing structure for a day ahead electricity market. The hybrid system consists of a wind farm and a pumped storage hydro unit. In this work, a small power system is considered as micro grid and it is expected that a hybrid system connected with the micro grid has a role to play to maintain the micro grid frequency. In this formulation, the optimum operating schedule of PSH unit in coordination with wind farm has been investigated. The pump storage hydro plant is operated to minimize UI flow by improving the operating frequency of the micro grid. The uncertainty on wind power prediction and loads of the micro grid are considered in this work. A new formulation of the problem has been presented and solved using Artificial Bees' Colony Algorithm (ABC). The solution of this algorithm gives the strategies to be followed by the hybrid system to operate its pump storage hydro unit under frequency based pricing environment. The effect of the initial water storage of the PSH unit on the performance of the system has also been investigated.

2. Frequency based pricing

The power system operation under reformed system structure has initiated a competitive environment in generation, transmission and distribution services. Frequency based pricing mechanism is a key feature in promoting competitiveness in electricity market structure [19]. Price based control issues of power system operation under new environment have already been reported in the literature [25]. There are several issues which make Indian power system operation unique and one among them is frequency linked pricing of energy. Before the implementation of frequency linked pricing mechanism, the Indian power system operation had been indisciplined. The grid used to suffer with abnormally low frequency during peak hours and high frequency during off peak hours. In other words, the overdrawal by the state utilities during peak hours had not been discouraged andsurplus generation during off peak hours had been encouraged. In order to overcome this, a new mechanism of pricing which is frequency linked; named as Availability Based Tariff (ABT) has been introduced in 2002. There are three components in ABT calculation; these are (i) Capacity Charge – linked to the plant availability and it is a fixed cost. The total payment made to the utility over a period of time is determined based on the average availability of the plant for that period. (ii) Energy Charge – linked to payment against schedule energy exchange which is a variable quantity and (iii) Unscheduled Interchange Charge – linked to the cost for deviation from the schedule, i.e. the charge for energy exchange in variation from committed schedule. This third component has been made frequency linked. In ABT structure, the cost of Unscheduled Interchange (UI) is made inversely proportional to the grid frequency [15]. When frequency is50 Hz or above, the utility will be paid less for surplus generation and thus the UI charge is kept small. On the other hand, the utility has to pay at very high UI charge for any overdrawal during the time when system prevailing frequency is less than 50 Hz. In ABT based structure, each hour is dibided into four time blocks of 15 min duration. The average frequency of this 15 min duration is used to determine the price of UI for each time block. For a total day thus, there are 96 time blocks. The UI charge as per Central Electricity Regulatory Commission (CERC) regulation has been detailed in Section 6 and used in this paper.

3. Problem formulation

In the proposed method, it is expected that the hybrid system will deliver energy to the micro grid as per the contractual agreement and will try to operate its PSH unit most optimally ensuring scope for further commercial activities. In each hour of the scheduling period, the total system load must be supplied by both central generators and hybrid system in order to maintain the micro grid frequency. The variability associated with the wind power generation or loads may influence the system operating frequency to drop/rise. To maintain the frequency, UI flows to meet the demand and the operating frequency would thus improve. The PSH unit is operated to minimize the payment for deviation from the schedule, i.e. UI charge by improving the operating frequency. However, the plant has to comply with its storage and operational limitations. The complete mathematical statement of the problem is written as.

Maximize

$$\sum_{t=1}^{24}\left(C_{SI}^t + C_{PS}^t - C_{PPL}^t - C_{PPP}^t\right) \tag{1}$$

Subject to

$$P_{HS}^t = P_W^t + P_H^t, \quad \forall t \in T \tag{2}$$

$$P_{HS}^t + P_{CG}^t - P_D^t - |V_i|\sum_{j=1}^{NB}|V_j|\{G_{ij}\cos(\theta_i-\theta_j) + B_{ij}\sin(\theta_i-\theta_j)\} = 0, \quad \forall t \in T \tag{3}$$

$$Q_{HS}^t + Q_{CG}^t - Q_D^t - |V_i|\sum_{j=1}^{NB}|V_j|\{G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)\} = 0, \quad \forall t \in T \tag{4}$$

$$P_{CG}^{\min} \leqslant P_{CG}^t \leqslant P_{CG}^{\max}, \quad \forall t \in T \tag{5}$$

$$P_{WU}^t \leqslant P_{WU}^{\max}, \quad \forall t \in T \tag{6}$$

$$D_{LU}^t \leqslant D_{LU}^{\max}, \quad \forall t \in T \tag{7}$$

$$E^{t+1} = E^t + \left(\eta_P P_P^t - \frac{P_H^t}{\eta_H}\right), \quad \forall t \in T \tag{8}$$

$$P_P^L \leqslant P_P^t \leqslant P_P^U, \quad \forall t \in T \tag{9}$$

$$P_H^L \leqslant P_H^t \leqslant \min\left(P_H^U, \eta_H \frac{E^t}{t}\right), \quad \forall t \in T \tag{10}$$

$$E^L \leqslant E^t \leqslant E^U, \quad \forall t \in T \tag{11}$$

$$\mathrm{UI}^t \leqslant \mathrm{UI}^U, \quad \forall t \in T \tag{12}$$

$$S_{ij}^t \leqslant S_{ij}^U, \quad \forall t \in T \tag{13}$$

$$\left|V_i^{\min}\right| \leqslant |V_i^t| \leqslant |V_i^{\max}|, \quad \forall t \in T \tag{14}$$

The objective function in Eq. (1) is formulated as profit of the hybrid system for supplying energy to the micro grid at every instant of 24 h period. The first component of the objective function is the hourly cost of schedule interchange; which is the product of hourly market price with the prescheduled power delivered to the micro grid and is expressed as

$$C_{SI}^t = c^t P_{HS}^t, \quad \forall t \in T \tag{15}$$

The energy delivered to the micro grid by the hybrid system or utility may differ than what was scheduled. If the actual energy supplied by the utility is higher or lower than the scheduled, the utility would receive payment for the excess energy supplied or would pay back for the energy short fall, at a rate dependent on the frequency at that time [15]. The second and third component of the objective function represent the hourly payment received by the utility due to excess energy supply and hourly payment that the utility has to pay back for energy shortfall respectively. These costs are measured with respect to the cost of UI and are calculated by multiplying the respective UI with cost of UI as shown in Eqs. (16) and (17) respectively.

$$C_{PS}^{t} = \mathrm{UI}_{PS}^{t} * Rate^{\mathrm{UI}}, \quad \forall t \in T \tag{16}$$

$$C_{PPL}^{t} = \mathrm{UI}_{PPL}^{t} * Rate^{\mathrm{UI}}, \quad \forall t \in T \tag{17}$$

UI charge is frequency dependent. For frequency calculation, the formula derived in [18] is modified and used in this work. For any hour 't', it is calculated by Eq. (18) as shown below.

$$f^{t} = 50 - \frac{P_{D}^{t} - (P_{CG}^{t} + P_{HS}^{t})}{PFR * P_{D}^{t}}, \quad \forall t \in T \tag{18}$$

In this work, the value of Frequency Fall Ratio (PFR) is adjusted to 4%. The fourth component of the objective function is the hourly cost of power consumed by the utility for pumping the water to the upper reservoir and is measured with respect to UI charge as shown in Eq. (19) below.

$$C_{PPP}^{t} = \mathrm{UI}_{PPP}^{t} * Rate^{\mathrm{UI}}, \quad \forall t \in T \tag{19}$$

The proposed optimization problem deals with several physical and operational constraints. Some of the constraints are handled separately interval wise during the optimization and some are handled in the optimization process taking all intervals into account. The actual power delivered by the hybrid system to the micro grid at a given hour 't' is given in Eq. (2) as sum of available wind power and hydro generation (if any) from the PSH unit.

For each interval (t), the total power generated by the hybrid system and central generators must be able to supply the total system demand and power loss. The power balance equations related to real and reactive power are expressed in Eqs. (3) and (4) respectively.

Eq. (5) describes the upper and lower generation limits of central generators. The wind power uncertainty and load uncertainty at any hour (t) must be lower than their maximum uncertainty limits and are expressed in Eqs. (6) and (7) respectively. Eq. (8) describes the energy balance in the reservoir. The reservoir energy at ($t+1$)th hour is equal to the available reservoir energy at tth hour plus pumping energy (if pumping) or minus the energy supplied to the micro grid load due to hydro generation. Eqs. (9) and (10) describe constraints associated with PSH unit operation. The reservoir energy level must not be lower than its minimum or more than its maximum energy levels and is expressed in Eq. (11). The flow of UI at any hour 't' must be less than the maximum allowable UI limit as shown in Eq. (12) and this is decided based on the maximum line loading considerations and resultant frequency variations. Other network operational constraints those must also be observed are given in Eqs. (13) and (14).

4. Pumped storage hydro plant operation strategy

The pumped storage hydro plant is a large scale energy storage technology. The aim of using the pumped storage hydro plant is conventionally to alleviate supply demand gap of hybrid electric systems. The wind-PSH plant coordinated operation under frequency based pricing must be different than the conventional approach. Here, the aim of PSH plant operation is not only to reduce the minute to minute unscheduled interchange but simultaneously to regulate the frequency of the grid as well. The operation of PSH unit is basically dependent on the following factors:

- The contractual agreement of power exchange between hybrid system and micro grid.
- The available wind power.
- The prevailing grid frequency.
- The storage reservoir constraints.

Based on the above information, an algorithm has been developed to decide the strategy to be adopted for the PSH unit operation. For Indian power sector, the most recent CERC regulation [26] proposed the frequency variations to be more stringent, between 49.7 Hz and 50.2 Hz. The details of the PSH unit operation schedule is shown in Fig. 1. There are six (06) operational boxes (1, 2, ..., 6) representing the PSH plant operation, where operation 1, 2 or 3 are the possible steps, if available wind power is more than contract power, while; operations 4, 5 or 6 are possible if the wind power is less than the contract values.

Operation 1: When there is surplus wind power and grid frequency is below 49.7 Hz, PSH plant is idle. It is proposed to sale the extra wind energy to the grid at a higher UI rate and this will result more profit for the hybrid system.

Operation 2: When there is surplus wind power and grid frequency is above 50 Hz, PSH acts as pump. It is proposed (i) to store the extra wind energy into hydraulic energy and (ii) to purchase power from the grid at lower UI rate for further pumping activity (if possible).

Operation 3: When there is surplus wind power and grid frequency is between 49.7 Hz and 50 Hz, PSH acts as pump. It is proposed to recover the extra wind energy into hydraulic energy.

Operation 4: When there is deficit wind energy and grid frequency is below 49.7 Hz, PSH acts as generator by converting its hydraulic energy into electric energy. It is proposed (i) to generate the deficit amount from its hydro turbine and (ii) to generate (if possible) and sale the extra power to the grid at higher UI rate.

Operation 5: When there is deficit wind energy and grid frequency is above 50 Hz, PSH operation is proposed to be either (i) as generator or (ii) as pump. The investigation with both the cases have been detailed in Section 6.

Operation 6:When there is deficit wind power and grid frequency is between 49.7 Hz and 50 Hz, PSH acts as generator by converting its hydraulic energy into electric energy. It is proposed to generate the deficit amount from its hydro turbine.

5. Solution algorithm and its implementation

Among the heuristic based search algorithms in the literature, ABC is a relatively new optimization algorithm [20,21] and the performance of ABC algorithm have been tested by some researchers in solving power system problems recently [22–24]. The performance of ABC algorithm in solving such non-linear multi-model, multi-dimensional power system problems, discussed above has been found to be satisfactory, promising and motivating. In the present work, the profit maximization of micro grid connected wind farm is a dynamic optimization problem and it is converted to hourly discretized optimization problem having both time related and time separated variables. It will be useful to solve this profit maximization problem using ABC based algorithm. As food source position in ABC algorithm represents possible solution,

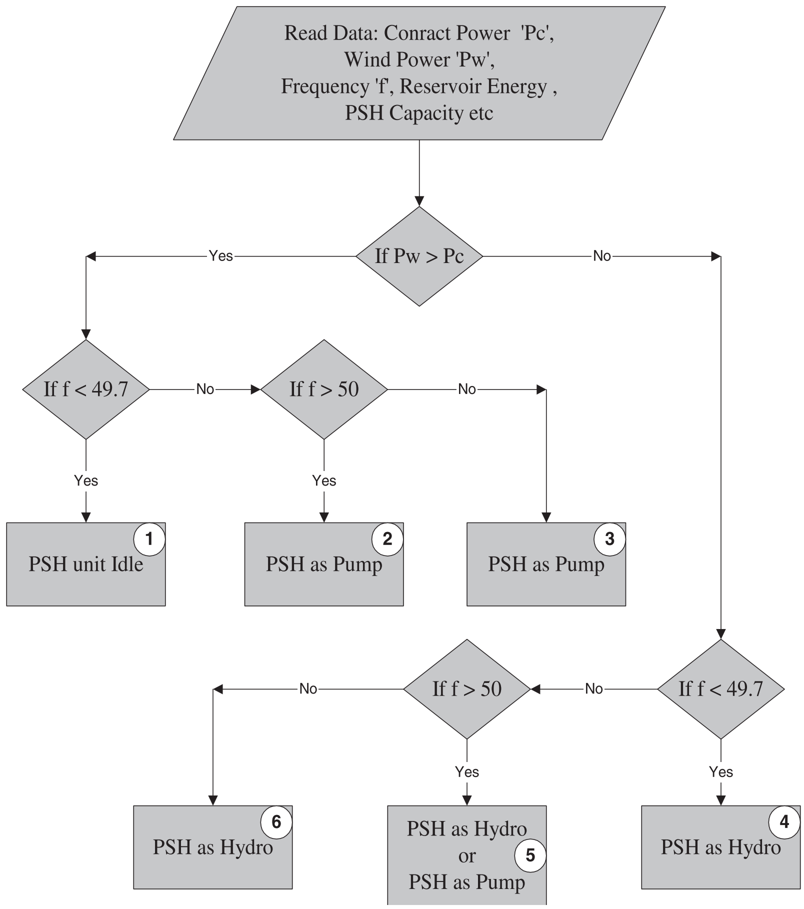

Fig. 1. Flowchart of PSH unit operation.

the food sources are assumed to be spread over the entire time horizon of 24 h. The following steps describe the details of implementation of the proposed method.

5.1. Initialization

The initial solutions (food source positions) x_{ij} generated in a random manner which consists of central generators power output (P_{CGt}), the wind power error (U_{Wt}) and load uncertainty (U_{Lt}) for each time period t as $x_{ij} = (P_{CG11}, P_{CG21}, U_{W1}, U_{L1}, \ldots, P_{CG1n}, P_{CG2n}, U_{Wn}, U_{Ln})^T$ where $j = 1, 2, \ldots, D$. D is the dimension of the vector which is the number of optimization parameter. Here, 'n' is maximum number of interval; here it is 24. Hence, the dimension of each solution vector is $D = 4 * n$. Here, $i = 1, 2, \ldots$, SN. SN represents the colony size of the honey bee swarm. In this work, SN is taken 20.

5.2. Evaluation of solution

With the initial random values of problem variables, the Newton Raphson load flow solution is executed to determine the schedule and unscheduled interchanges (if any) between the utility and the micro grid for each time period t. For operation of PSH unit in next interval, the energy level in the upper reservoir and the prevailing micro grid frequency are calculated using Eqs. (8) and (18) respectively after the end of each period t. The costs of scheduled and unscheduled interchanges are calculated along with the cost of power sold, cost of pumping, etc. The operational gain of the utility for each time period t is calculated using Eq. (1) and then adding for 24 h period gives the total profit for the utility.

5.3. Employed bee phase

New solutions (problem variables) Y_{ij} in the neighborhood of X_{ij} are generated for the employed bees' by $Y_{ij} = X_{ij} + \theta_{ij} * (X_{ij} - X_{kj})$ and are evaluated in the same process discussed above. The greedy selection process is performed between Y_{ij} and X_{ij}. Where θ_{ij} is a random number. The information about the operational gain of the solutions are shared by the employed bees with the onlookers for further foraging; which ensures collective intelligence in the search process.

5.4. Onlooker bee phase

New solutions are generated for the onlooker bees' based on the probability p_i for the solution X_i using $p_i = \frac{fitness_i}{\sum_{j=1}^{N} fitness_j}$. Where $fitness_i$ is the fitness value of the solution i, which is proportional to the nectar amount of the food source position or problem variables i. In this work, $fitness_i = \sum_{t=1}^{24} (C_{SI}^t + C_{PS}^t - C_{PPL}^t - C_{PPP}^t)$. The solution is evaluated the same manner as discussed above and greedy selection is performed between new and old solutions. In this process, the onlookers explore for better solutions with higher probability.

5.5. Scout bee phase

The solution i, if found inferior, is declared as abandoned and is replaced with new randomly produced solution or variables for the scout by the following formula $x_i^j = x_{\min}^j + rand\left(x_{\max}^j - x_{\min}^j\right)$.

In this work, the limit for abandonment or trial counter is chosen 100 to improve a solution.

Save best solution.

The best solution (food source positions) is memorized and retained which comply with

(i) highest operational profit for the entire period of 24 h and
(ii) all limiting conditions.

5.6. Stopping criteria

Stop when Maximum Cycle Number (MCN) is reached. It is decided based on experience and in this work, the value of MCN is chosen 200.

6. Test systems and results

In order to apply the proposed method, the test system used in [13] has been referred and modified as shown in Fig. 2. The network parameters and bus data are mentioned in Tables 1 and 2 respectively. The system under study consists of six bus transmission system connected with a four bus distribution system with the help of a 100 MVA transformer. The transmission system consists of two central generators CG_1 and CG_2 with capacity of 250 MW and 500 MW respectively. The hybrid system is having a wind farm and one Pump Storage Hydro (PSH) unit with reversible pump turbine. The wind farm generation capacity is taken as 59.4 MW [13]. The wind farm is modeled as Fixed Speed Wind Generating System. The capacity of the PSH unit is considered to be known in the present analysis. For a combined wind-hydro system in a smaller power system, the installed capacities of wind farm and PSH unit are quite similar [4–6]. A PSH unit [6] of 1.5 MW up to 15 MW hydro turbine nominal powers with 60 MW h water reservoir capacity is found to be compatible with a wind farm of 59.4 MW. The hybrid system is connected to bus 10. The load demand of each bus of the micro grid is assumed to be time varying [13] and is discretized in time by multiplying each bus load with the load scaling factor as shown in Fig. 3. The available wind power for 24 h period is taken from [13] and is reproduced in Fig. 4. Further, an uncertainty up to 5% in load demand and 5–10% in wind power, have been considered.

The aim of the hybrid system is first to dispatch the power to the micro grid as per the hourly contractual agreement of power transaction and second to utilize its PSH unit to reduce the UI flow between utility and micro grid. However, it is assumed that maintaining micro grid frequency is a collective responsibility of both central generators and hybrid system. The hourly contractual agreement is plotted in Fig. 5, for total energy supply of 299 MW h and hourly market price for schedule power transaction is mentioned in Table 3.

The Grid operation under ABT environment suggests to measure the peak load after every 15 min time block to calculate frequency and also suggests the corrective dispatch that is required to be done. Therefore, there are actually 96 time blocks available for a period of 24 h. That means the UI rates are measured four times in an hour. In order to limit the dimension of the problem we first assume that the load is fixed for 1 h duration considering its uncertainty and generation is also assumed unchanged. Hence, the frequency measurement and UI charge calculation are performed once in 1 h. Therefore, in our initial calculation, the optimization

Table 1
Transmission line data.

From bus to bus	Resistance (p.u.)	Reactance (p.u.)	Line charging (y/2) (p.u.)
1–2	0.021	0.1097	0.004
1–6	0.0824	0.2732	0.004
2–5	0.107	0.3185	0.005
3–4	0.0945	0.2987	0.005
3–5	0.0662	0.1804	0.003
4–5	0.0639	0.1792	0.001
4–6	0.034	0.098	0.004
6–7	0	0.1	0
7–8	0.054	0.082	0
8–9	0.054	0.082	0
8–10	0.054	0.120	0

Table 2
Bus data (all values are in p.u.).

Bus	$P_{G(\min)}$	$P_{G(\max)}$	P_D	Q_D	$Q_{\max}$	$Q_{\min}$
1	0.5	2.5	0.92	0.29	1.5	−0.2
2			0.78	0.39	0	0
3	1	5	0.73	0.19	3	−0.2
4			0.67	0.24	1	0
5			1.12	0.31	1	0
6			0.26	0.12	0	0
7			0.1	0.02	0	0
8			0.15	0.05	0	0
9			0.1	0.03	0	0
10			0.02	0.0125	0	0

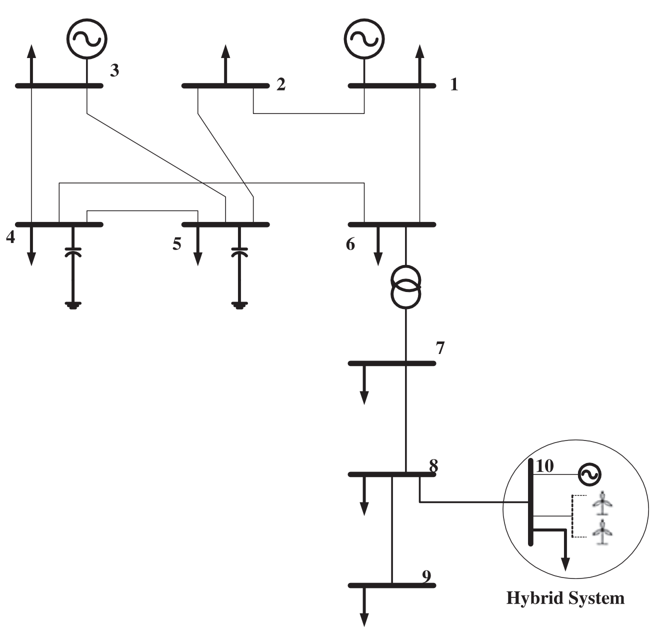

Fig. 2. The test system.

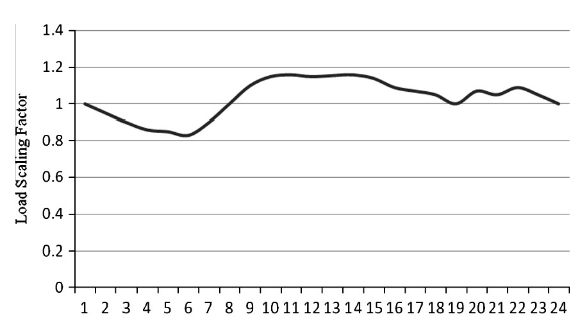

Fig. 3. The load variations.

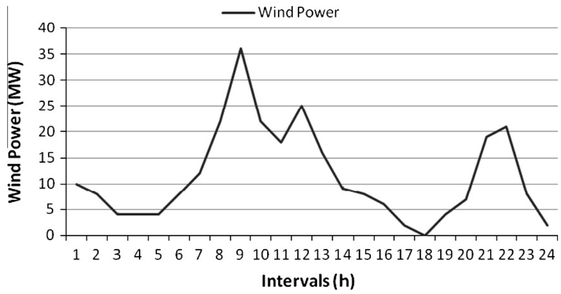

Fig. 4. The wind power scenario.

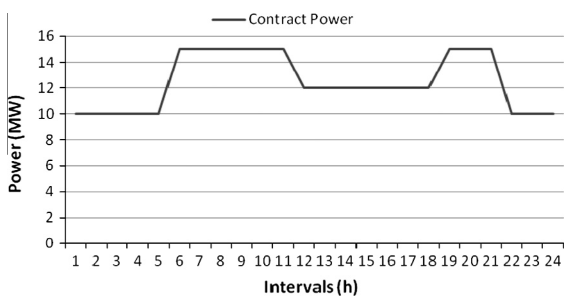

Fig. 5. The hourly contractual agreement between hybrid system and micro grid.

Table 3
Contractual rate for schedule interchange.

Time	Rate (Rs/MW h)
00.0–07.00 and 21.00–24.00	5500.00
08.00–20.00	11000.00

problem is having only 24 time blocks instead of 96. However, 15 min average simulations also have been carried out considering 96 intervals in the second part of our investigation. The UI charge as a function of frequency used in this work has been referred from the most recent CERC regulation [26], and is plotted in Fig. 6.

The pumped storage hydro plant operational strategy has been detailed in Section 4. It is mentioned that the PSH unit operation is based on six different conditions. Out of them, operating condition 5 proposes two mode of operations for the PSH unit; either as hydro or as pump. It is important to know which mode of operation would result more profit for the owner of the hybrid system. Hence, it is worth investigating both the possibilities of PSH plant operation under condition 5. In this work, the problem has been solved for both the cases of PSH unit operation for condition 5 and compared. In Case 1, the PSH plant is operated as hydro generator and in Case 2, the PSH plant is operated as pump.

The optimization starts with the values of average hourly available wind power considering uncertainty, initial reservoir energy level, initial operating frequency of the micro grid, power of central generators, micro grid load demand and searches for the strategy to be adopted by the utility to operate its PSH unit. The initial reservoir energy level is considered full, i.e. 60 MW h and micro grid initial operating frequency is assumed as 49.99 Hz. The variables considered in each time block are central generators power output, load uncertainty and wind power uncertainty.

6.1. Case-1: PSH plant operated as hydro under condition 5

The hybrid system during its optimization, tries to deliver the hourly energy to the micro grid as per its prescheduled contractual agreement but in practice, the uncertainty in wind power prediction, load change in the system, hydro constraints, etc., may make the actual power dispatch different from the prescheduled. The solutions of the optimization algorithm show how the actual hourly power delivered by the utility tried to follow the prescheduled contract power and this fact is evident from Fig. 7. Under ABT environment, when the utility is able to deliver energy to the micro grid as per the scheduled, there is no UI flow and hence no UI charge. However, if the actual energy supplied is lower/higher than what was scheduled, there will be UI flow between utility and micro grid. Hence, the UI charge will be imposed depending on the prevailing frequency of the grid. The UI flow may be positive or negative. Positive UI flow represent the instances when surplus power was supplied to the micro grid, whereas, negative UI flow represent the instances when extra power was purchased from the grid generators by the utility. It is observed from Fig. 7 that there are three instances when UI flow is positive and there are five instances when UI flow is negative. For example, during ninth

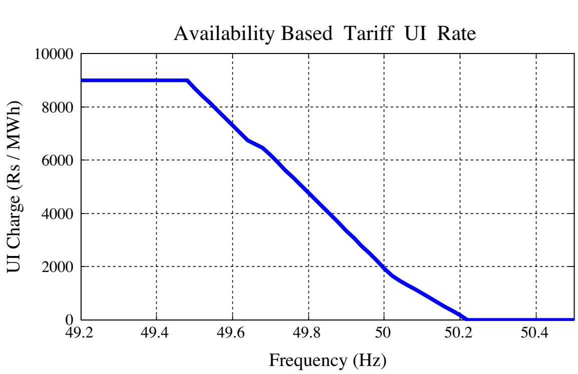

Fig. 6. The unscheduled interchange rate under ABT.

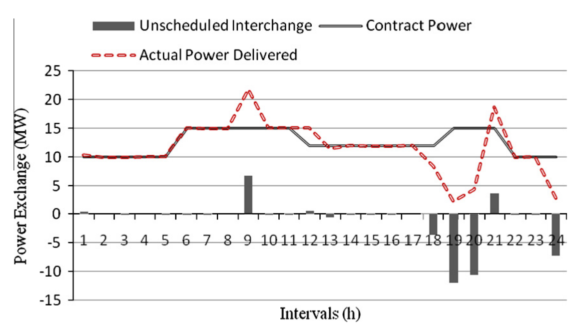

Fig. 7. The actual power delivered and UI for Case 1.

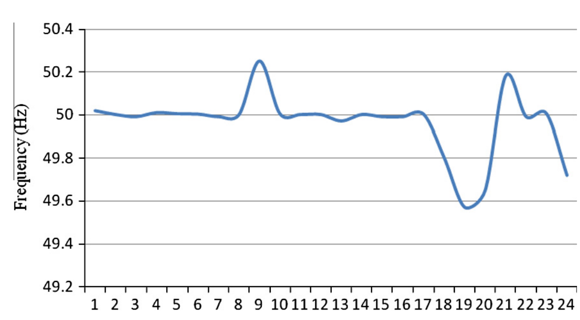

Fig. 8. The hourly average frequency for Case 1.

interval, the actual power delivered was 21.77 MW instead of pre-scheduled value of 15 MW, which resulted 6.77 MW UI flow from the utility to the micro grid. On the other hand, during 20th interval the actual power delivered was 4.4 MW instead of 15 MW. As a result, an amount of 10.6 MW UI flow resulted from the central generators.

The frequency at the end of each interval is calculated using Eq. (18) as discussed in Section 3. The hourly frequency is utilized to compute the UI charge for the current interval and moreover, the operation of the PSH Unit in the next interval is also decided based on this frequency. Therefore, it is important to know the hourly average frequency and hence, it is plotted in Fig. 8. In order to trace the variations in frequency between intervals, the frequency is calculated for every 15 min time gap between two successive intervals as intermediate frequencies and plotted in 24 h time scale and shown in Fig. 9. It is observed that most of the instances frequencies were maintained near 50 Hz and except few, the frequency variations were mostly within permissible range. Fig. 9 depicts the scenarios of unscheduled interchange with corresponding micro grid frequency. It is evident from the figure that during the periods of high UI flow, the frequency variation were large, which is obvious. For example, during 9th interval, the frequency is raised up to 50.25 Hz because of 6.77 MW UI flow to the micro grid. On the otherhand, during 18th, 19th, 20th and 24th intervals, because of energy supply shortfall, the micro grid frequency falls. The lowest frequency reported is 49.57 Hz during 19th interval.

To maintain the frequency within permissible range, the optimization algorithm allows the PSH unit to operate as per the requirement mentioned above and also selects when and what amount of generation/pumping is to be done. The complete PSH unit activities throughout the scheduling period and its corresponding reservoir energy level are shown in Fig. 10. The positive powers of PSH unit correspond to the intervals of generating action and the negative powers correspond to the intervals of pumping operation. During generating periods, the power is sold to the micro grid either at contractual rate or at higher UI rate. Whereas, during pumping periods, either the extra wind power is stored as hydraulic energy or the power is purchased from the micro grid for energy storage purpose at lower UI rate. The intervals of generation would cause fall in reservoir energy level and intervals of pumping would result raise in reservoir energy level. This fact is evident from Fig. 10.

6.2. Case-2: PSH plant operated as pump under condition 5

In this case, the problem is solved with same initial conditions as considered in Case 1. The only difference here is that the PSH plant operates as pump under operational condition 5. The detail results are presented in the following figures. Fig. 11 shows the actual power delivered against the contractual agreement and corresponding UI. The hourly average frequency is plotted in Fig. 12. The actual UI flows with frequency variations are traced in 15 min intervals and plotted in 24 h scale as shown in Fig. 13. The PSH activity and corresponding reservoir energy level is mentioned in Fig. 14.

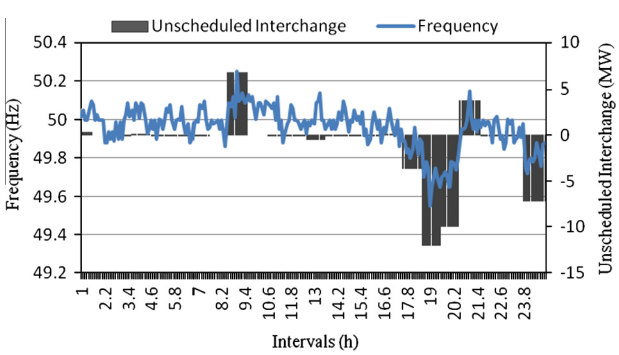

Fig. 9. The micro grid frequency and UI for Case 1.

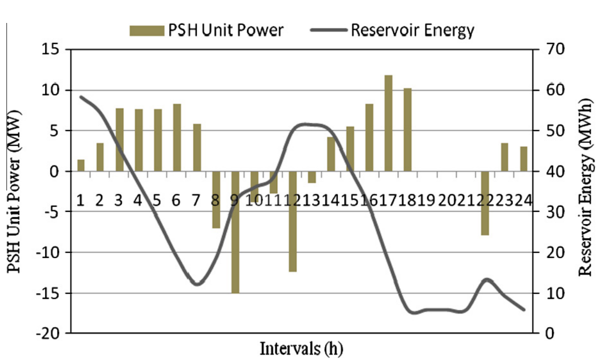

Fig. 10. The PSH plant activity and reservoir energy for Case 1.

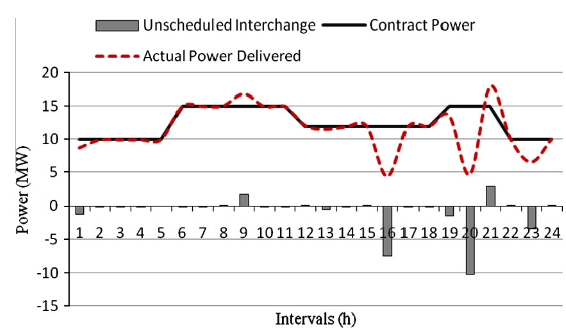

Fig. 11. The actual power delivered and UI for Case 2.

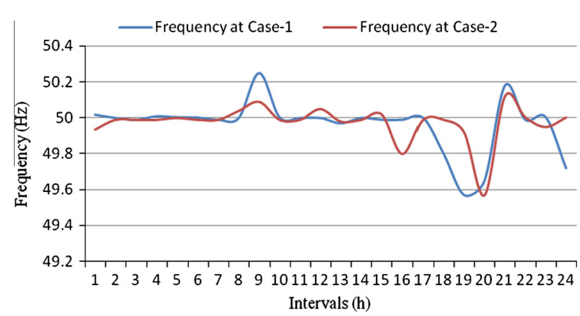

Fig. 12. The comparison of hourly average frequency.

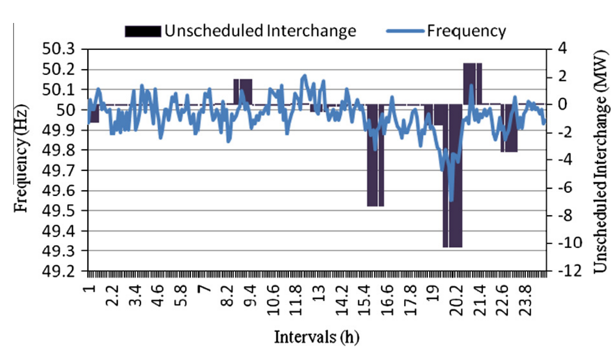

Fig. 13. The micro grid frequency and UI for Case 2.

Comparing Figs. 7 and 11, it is observed that the magnitude of UI is reduced in Case 2 and hence the frequency variations should be less in Case 2. In this operative schedule of PSH plant, the reported maximum frequency is 50.12 Hz and minimum frequency is 49.57 Hz. This fact is evident from Figs. 12 and 13. From the comparison on average hourly frequencies for both the cases reported in Fig. 12 show that frequency variations are less in Case 2. The PSH unit activity schedule is shown in Fig. 14. Comparing the PSH unit activities between both the cases, it is found that the number of pumping activity is more in Case 2 which ensures more storage reserve. The comparison in terms of energy exchange and operational gain are presented in Tables 4 and 5 respectively.

It is noted from the comparison that the PSH unit operation mode under Case 2 results more profit for the hybrid system because of reduced unscheduled interchange, more effective utilization of reservoir energy, less frequency variations and better power management.

The operation of PSH unit depends on the available wind power and the grid prevailing frequency. The wind power scenarios vary in different day, month or season. However, it may be the interest of many utilities to focus on the minute to minute energy transaction under the scenarios of varying load, frequency and volatile wind power. Therefore, it is important for the operator to know the required minute to minute activities of the PSH unit. According to ABT, the energy prices are determined based on the average frequency of 15 min time blocks. Therefore, in the present study of finding optimum scheduling of PSH unit combined with wind farm should be reviewed once in every 15 min. Moreover, the minimum transition time of the PSH unit to shift from one mode to other must be obeyed.

In order to show the minute to minute output power variations of the hybrid system for a complete day, a large volume of data to be handled and reported. Considering this fact, we have adopted a compromise here by initially presenting the problem based on hourly analysis for a complete day and then, analyzing the same problem based on 15 min interval. For this purpose, the problem has been extended up to 96 intervals each of 15 min durations for the entire 24 h period. The variations in load demand and wind power are kept fixed for every15 min duration throughout the day. Other input data like grid prevailing frequencies and reservoir energy levels are required at the end of every 15 min interval for the optimization to proceed. The dimension of the problem has now been increased to four times than the hourly average simulation. The optimization problem is solved by considering the PSH unit operation as Case-2. Simulation results in Fig. 15 show that the operation of PSH unit has varied during the entire 24 h period in order to meet the prescheduled contractual agreement with the micro grid under varying load conditions. In the present analysis, the transition time of PSH unit operation to shift from one mode to other has been considered as 30 min. It is evident from Fig. 15 that PSH unit has been kept null between 7 h and 7.30 h for a required mode shift operation. Similar transition time has been obeyed by the PSH unit during its other mode shift operation as shown in Fig. 15. The detail analysis regarding the energy exchange and operational gain with this 15 min average simulation are presented and compared in Tables 4 and 5 respectively.

In the analysis performed so far in both Case-1 and Case-2, the initial reservoir energy level was considered full at the beginning of the day. From the analysis it is revealed that the PSH unit exploits

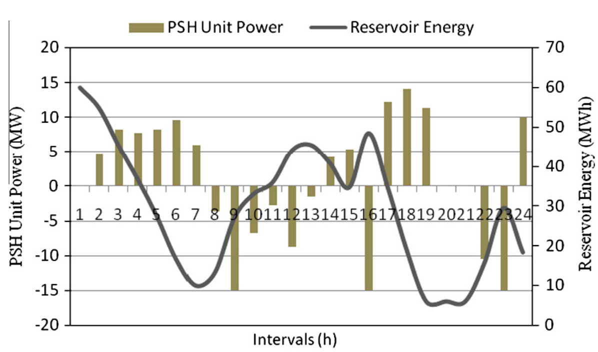

Fig. 14. The PSH plant activity and reservoir energy for Case 2.

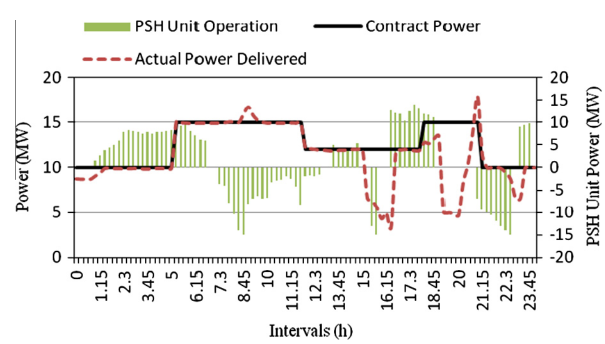

Fig. 15. The actual power delivered and PSH activity for Case 2 with 15 min. simulation.

Table 4
Comparison of energy exchange for a contract of 299 MW h energy.

Sl. no.	Particulars of energy	Case-1	Case-2	
		Hourly average simulation	Hourly average simulation	15 min average simulation
1	Actual energy supplied	278.389 MW h	279.17 MW h	278.57 MW h
2	Total unscheduled interchange	22.28 MW h	19.85 MW h	20.69 MW h
3	Resultant energy exchange	**300.66 MW h**	**299.02 MW h**	**299.26 MW h**

Table 5
Comparison of operational gain.

Particulars of cost	Case-1	Case-2	
	Hourly average simulation	Hourly average simulation	15 min average simulation
Cost of scheduled power dispatch	Rs. 2423307.00	Rs. 2518720.00	Rs. 2518601.00
Cost of power sold to the grid as UI	Rs. 38937.17	Rs. 22073.5	Rs. 21621.35
Cost of power purchased for load	Rs. 132894.00	Rs. 58560.00	Rs. 62296.00
Cost of power purchased for pumping	Rs. 139202.70	Rs. 169782.50	Rs. 167795.7
Profit	**Rs. 2190147.47**	**Rs. 2312451.00**	**Rs. 2310130.65**

the initial stored hydraulic energy in maximizing the hybrid system operational gain. It is evident from Fig. 10 that PSH unit delivers 42 MW h of energy from 0 h to 7 h under Case-1 from its initial stored hydraulic energy. Whereas, the same PSH unit delivers 44 MW h of energy from 1 h to 7 h under Case-2 from its initial stored hydraulic energy. The end reservoir energy levels were lower in both the cases, although for Case-2 it was slightly higher. It gives a natural suggestion to verify the operational gain of the hybrid system when it starts the day with an almost empty reservoir.

In view of this, an average hourly simulation was carried out to investigate the operational gain of the hybrid system starting with an almost empty reservoir of 10 MW h stored energy. The PSH unit is operated as Case-2 and other initial conditions were kept same as in Case-2. The variations in hourly average frequencies are shown in Fig. 16 and compared with the case when initial reservoir energy level was full. It is noted that because of shortage of stored initial hydraulic energy, the unscheduled interchanges were more in the initial hours and as a result the frequency fluctuations were more. However, in the latter part of the day the frequency variations were reported to be very close to the case with full initial reservoir. The PSH unit operation and corresponding variations in reservoir energy level are shown in Fig. 17.

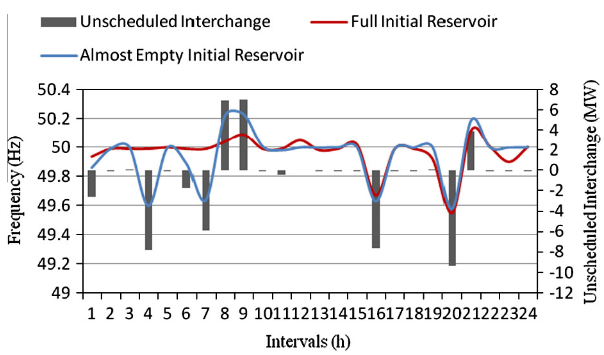

Fig. 16. The hourly average frequency comparison and UI for Case 2 with low initial reservoir.

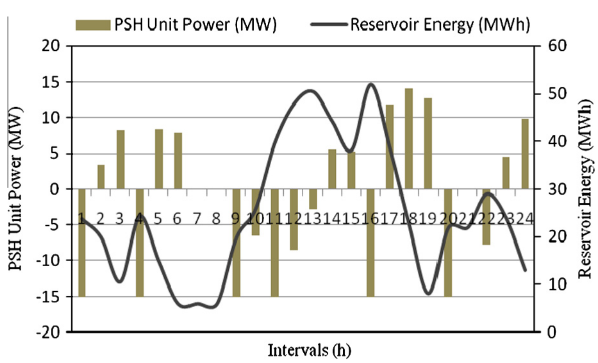

Fig. 17. The PSH plant activity and reservoir energy for Case 2 with low initial reservoir.

For comparison of operational gain of the hybrid system between the cases with full initial reservoir and almost empty initial reservoir, we must have to subtract the cost of initial stored hydraulic energy from both cases reported earlier with full initial reservoir. The detail calculation of overall profit of the hybrid system with full initial reservoir and almost empty initial reservoir are presented in Table 6 below. It can be noted from the comparison that low initial storage volume has an adverse effect on the frequency variation and economy of the hybrid system. However, there is not much sacrifice on the profit. This has become possible because the plant operation is made dependent on both available wind power and grid prevailing frequency, under frequency based pricing environment.

7. Conclusion

A new formulation and optimization approach has been presented to maximize the operational benefit of a micro grid connected hybrid system having wind farm and pumped storage hydro facility for a day ahead electricity market in a frequency based pricing environment. The pricing system considered follows the structure where the excess energy interchange between the utility and the micro grid known as unscheduled interchange has been charged under ABT rate structure. In the mathematical formulation, the essential electrical and hydraulic constraints are considered. It can be noted from the study that under frequency based pricing mechanism the operational strategy of PSH unit is different from the conventional wind-pumped storage plant operation. Here, the PSH unit operational strategy is designed based on two fold objectives: one, to compensate the energy imbalances of wind farm in meeting the prescheduled contractual agreement and second, to participate in the energy transaction with the grid in order to maximize the system economy. In the present work, two different approaches of PSH unit operation is analyzed and compared. It reveals that the PSH units would not operate simply to compensate for the short fall or the surplus generation of the wind units in a frequency based pricing system. Rather, the pump storage units should take the advantage of the low price periods to maximize the profit of the hybrid system. The simulation results indicate that the hybrid system can take part in system frequency control and simultaneously increase its profit by choosing a proper scheduling strategy for its PSH unit. Simulations have been performed considering both hourly and minute basis variation of loads and frequency. It appears that hourly simulations can produce a good approximation of the detailed simulations. Detailed simulation, however, can reveal the scenarios which are much closer to the actual ones, though requiring longer computing times. The differences between the approximated hourly simulation results with those based on detailed variations are due to the operational

Table 6
Comparison of overall operational gain.

Particulars	Case-1	Case-2	
	With Full Initial Reservoir	With Full Initial Reservoir	With Empty Initial Reservoir
Cost of scheduled power dispatch	Rs. 2423307.00	Rs. 2518720.00	Rs. 2430441.00
Cost of power sold to the grid as UI	Rs. 38937.17	Rs. 22073.5	Rs. 58660.80
Cost of power purchased for load	Rs. 132894.00	Rs. 58560.00	Rs. 81948.13
Cost of power purchased for pumping	Rs. 139202.70	Rs. 169782.50	Rs. 220833.10
Profit	Rs. 2190147.47	Rs. 2312451.00	Rs. 2186321.00
(Less) cost of initial stored energy	Rs. 94012.80	Rs. 98208.00	–
Overall profit	**Rs. 2096134.67**	**Rs. 2214243.00**	**Rs. 2186321.00**

constraints imposed on the too frequent variation in the operating modes of the PSH unit.

Simulations have also been performed to study the impact of the initial storage volumes of the PSH unit on the performance of the hybrid system. It has been found that low initial storage volume has an adverse effect on the frequency variation and economy of the hybrid system. Thus, the PSH units should be operated to maintain an optimum reservoir storage level such that the hybrid system may exploit the low priced periods to maximize the system economy.

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