A Joint Scheduling Optimization Strategy for Wind and Pumped Storage Systems Considering Imbalance Cost & Grid Frequency in Real-Time Competitive Power Market

Subhojit Dawn*‡, Prashant Kumar Tiwari*, Arup Kumar Goswami*

*Department of Electrical Engineering, National Institute of Technology Silchar, Cachar, Assam-788010, India.

(subhojit.dawn@gmail.com, prashant081.in@gmail.com, gosarup@gmail.com)

‡ Corresponding Author; Subhojit Dawn, Tel: +91 8720950139, subhojit.dawn@gmail.com

Received: 31.05.2016 Accepted: 28.06.2016

Abstract- This paper presents a simple and efficient operating strategy for the operation of Pumped Storage Hydro (PSH) plant so as to maximize the profit of the Wind-Thermal-PSH hybrid plant with considering the grid frequency (f) and current energy level of the PSH plant. The wind speed is predicted for a day-ahead market and with this predicted value of wind speed the wind plants are committed to supply the demand. If there is a difference between the predicted and actual wind power output, the PSH is operated in order to reduce this difference and trying to minimize the effect of imbalance cost, which is occurred due to the mismatch between the actual and predicted data. Thus the combined operation of wind, thermal and PSH helps to reduce the uncertainty of wind power in economic manner under completely deregulated power market. Two new energy levels (E_{opt} and E_{low}) for pumped storage have been also incorporated in this work to maximize the profit and revenue of the system. The proposed strategy is implemented using MATLAB Interior Point Solver (MIPS) to solve the optimal power flow problem. The implementation has been done on modified IEEE 30 bus system. The results of proposed approach have been compared with an existing strategy to show the effectiveness of the proposed approach.

Keywords Imbalance Cost, Market Clearing Price, Pumped Hydro Storage, Competitive Power Market, Load Scaling Factor.

1. Introduction

During the last few years, old monopoly regulated electricity compositions are substituted by the deregulated electricity compositions. A competitive environment is established between Generation Companies (GENCOs), Transmission Companies (TRANSCOs) and Distribution Companies (DISCOs) after initiating deregulation in the electricity market, and consumers have the benefit of this competition. In this new environment, global climate change is one of the greatest environmental concerns. The only way to overcome or to reduce this calamity is to cut-off the level of greenhouse gases. Many different measures have been adopted worldwide to limit the greenhouse gas emission and thus to reduce the harm to the environment. Many developing countries introduce various initiatives to stabilize carbon dioxide emissions in a sustainable level. Electric power sector is one of the major sources of greenhouse gas emission. To reduce this gas emission, renewable energy sources has taken the important role in recent years [1]. Wind & solar energy is one of the clean sources which give the emission free electrical power to end users. For independent, environmental, reliable, financial and social reasons many people choose to use wind power as the replacement of conventional energy sources. But, the output of the renewable energy sources (mainly wind & solar) are variable and uncertain in nature, which may create a security and stability problem of an electrical system. Some additional energy sources are required with renewable energy sources for balancing and maintain the power supply [2,3]. Due to the highest efficiency, reliable operation and recycling process of raw material; pump hydro-storage system has been used mostly as energy storage throughout the world. Another solution to overcome the unpredictable nature of wind is to use different forecasting techniques for the prediction of wind speed based on the historic data. There are different techniques like ANN, HHT or Weibull Probability distribution have been used for forecasting the wind data and try to minimize the effect of uncertainty in the electricity market. Even with forecasting techniques there is a certain level of uncertainty involved, so better method to overcome the intermittency of wind is to combine the above two methods that is use both prediction and energy storage techniques. Paper [4] presents a methodology for improving the power availability and profit by the hybrid operation of wind power and pumped storage units. There are other different energy storage devices which can be used with wind firm like battery storage or flywheel etc. but the most suitable in terms of power storage capacity and cost effectiveness should be PSH. References [5,6,7] have discussed some approaches related to the operational difficulties and the feasibility of Wind-PSH hybrid plants. Paper [8] gives an operating strategy for maximizing the profit of a wind-PSH hybrid plant in a frequency-based pricing environment. Ma *et al*. [9] proposed a solar-wind-pumped storage hybrid system for an isolated micro-grid to optimize the system design and maximize economical & technical feasibility of the system. An energy dispatch model is presented in [10] for a renewable hybrid system to minimize the fuel consumption cost of the system by amplifying the operation of wind turbine, solar photo-voltaic and storage system. Paper [11] depicts an approach to optimal allocation of energy storage in a deregulated power market by using probabilistic OPF, to minimize social cost for every hour. Joint operation of wind farms, pump-storage, photo-voltaic and energy storage devices is studied in [12] for maximizing the profit with considering uncertainties in wind and photovoltaic. Paper [13] presents the modelling, control and performance of a micro-grid, connected to the utility under variable load demand and different environmental conditions. Ma *et al.* [14] presents an approach to minimize the system cost and maximize the reliability of power supply by optimal modelling, sizing of pumped-storage based standalone photovoltaic power systems. Paper [15] depicts the effect of improper placement and size of energy storage on the system cost. Hybrid multi-objective particle swarm optimization has been used by the authors for solving the optimal power flow problem in this work. Murage *et al.* [16] study the economic benefit of optimal use of wind integrated pumped hydro storage system in Kenya.

After the comprehensive literature review it has been found that the following points still require to be answered: (a) what are the economic impacts of wind integrated deregulated power system? (b) how imbalance cost effects the competitive power market? (c) what are the impacts on system profit due to the mismatch between the forecasted and actual wind speed in a power system? (d) how use of storage devices are beneficial for hybrid operation of renewable energy sources? (e) how grid frequency can maintain by operation of wind-storage hybrid system. Although, many researchers have pointed out various techniques or phenomenon to solve several problems regarding the operation of renewable-storage hybrid power plant but still there are some provisions to maximize the profit in a large scale of the electrical system, by generation scheduling of thermal & wind plant and energy level scheduling of PSP plant.

In this paper an efficient operating strategy of wind-thermal-pumped storage hybrid system has been proposed, which is different from the operating strategy suggested in Reference [8] and the comparison has been done for both the strategies with considering the objective function of maximization of revenue generated from PSP plant & thermal plant and maximization of profit of the hybrid system. The comparison is done only with regard to operating strategy of pump storage units, the operational methodology and some constraints are entirely different from the Reference [8]. In this work, wind speed forecasting has been done for a day ahead electricity market and the power output for these wind speeds are calculated using the characteristic graph of wind (Shown in Fig. 1, where V_{ci} is the cut-in wind speed, V_r is the rated wind speed and V_{co} is the cut-out wind speed). In this work, we assume the value of V_{ci}, V_r and V_{co} as 3 m/s, 15 m/s and 26 m/s respectively.

Based on this predicted wind power it is assumed that the wind farm will be committed to supply the predicted power output; but if the actual power is different from the predicted one then PSH has to operate to minimize the effect of imbalance cost. The operation of pump-hydro system in pumping or generating mode is mainly depends on three factors i.e. predicted & actual wind power, frequency of the grid at that instant and energy level of PSH plant. The presented strategy of PSH operation using these three factors, will help to maximize the net revenue and profit of wind-thermal-PSH hybrid plant.

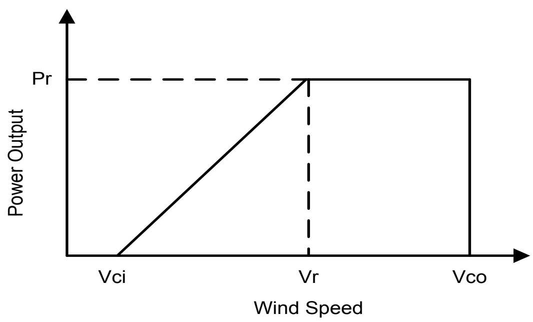

Fig. 1. Power Output Characteristics vs. Wind Speed

2. Mathematical Formulation

Modelling of pumped hydro storage, formulation of market clearing price and locational marginal pricing has been considered in this work for obtaining the objective function.

2.1. Operation of Proposed Hybrid Wind-Thermal-Pumped Storage Hydro Power Plant

System design is a very crucial step before the simulation, optimization and orientation of result. The proposed wind-thermal-pumped storage hybrid power plant is demonstrated in Fig. 2. The prime constituents of this system are - power generation (wind park and thermal power plant), storage system (pumped-hydro plant with upper basin and lower basin), energy demand (electricity consumption), transmission system (electricity grid) and control station. Four energy levels are considered for upper basin of PSH plant (E_{max}, E_{opt},

E_{low} and E_{min}) in this work for maximization of system revenue and profit. Actual, predicted wind speed data and grid frequency have been used for operation of storage system. If a mismatch occurred between the actual and predicted wind speed data, after completing the power delivery contracts between GENCOS and DISCOS; then GENCOS may be awarded or penalized by DISCOS for their surplus or deficit supply of power.

This model has been developed for minimizing the effect of uncertainties of wind power by generation scheduling of thermal & wind power plant and energy level scheduling of the upper reservoir of the pump-storage system. When predicted wind speed (PWS) is greater than the actual wind speed (AWS), then PSH plant is operated as a generator to fulfil the power demand and when AWS is greater than the PWS then PSH plant acts as a pump for store the energy for future use. Optimal operation of PSH plant can also give the stability in grid frequency by changing their operation mode. If the AWS is greater than PWS as well as grid frequency and energy level of PSH is in the stable condition, then total demand from the thermal power station has been minimized by that amount of power, which is the difference between the power generated from the AWS & PWS and that amount of power has been supplied by the wind power plants. For these operating phenomenon, profit of the hybrid system is maximized (because of wind power has lower cost as compared to thermal power).

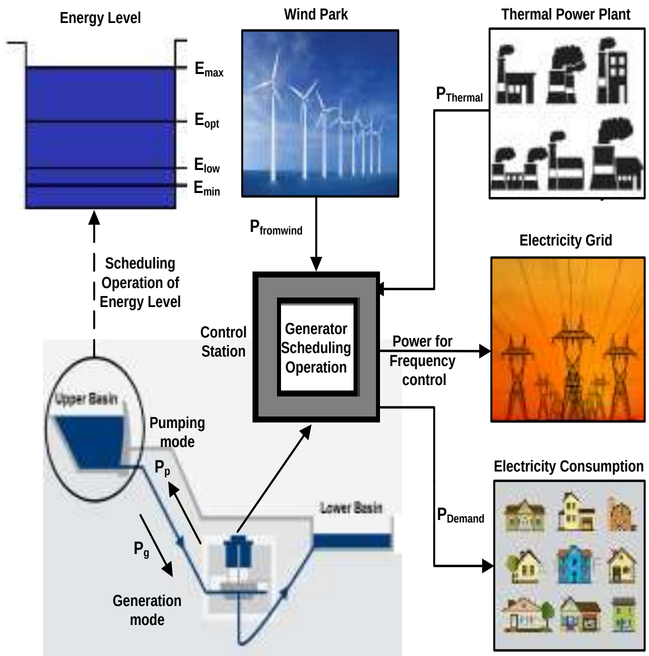

Fig. 2. Schematic Diagram of Proposed Hybrid Power Plant

2.2. Pumped-Hydro Storage Power Plant

The most consequential variables for the operation of pumped-hydro storage power plant are the capacity of upper basin and difference of heights between the upper & lower basin. Pumped-hydro storage power plant can operate in any mode – generating or pumping [14]. PSH plant is operate as a generator in the Peak-demand hour and acts as a pump at the Off-peak demand hour.

- *Generating Mode*

This is also called the discharging mode. In this period, PSH unit has generate power for fulfilment of power demand. The generated power from the PSH unit can be demonstrated as:

$$E_g = \rho g h V_g \xi_g \tag{1}$$

Where, 'ρ' is density of water, 'g' is acceleration due to gravity, 'h' is head or difference in the elevation of reservoirs, 'V_g' is volumetric flow rate of water during generation mode and 'ξ_g' is conversion co-efficient for power generation.

- *Pumping Mode*

This is also called the charging mode. In this period the energy input for pumping operation of PSH can be demonstrated as:

$$E_p = \frac{\rho g h V_p}{\xi_p} \tag{2}$$

Where, 'ρ' is density of water, 'g' is acceleration due to gravity, 'h' is head or difference in the elevation of reservoirs, 'V_p' is volumetric flow rate of water during pumping mode and 'ξ_g' is conversion co-efficient for pumping operation.

2.3. Locational Marginal Pricing (LMP)

LMP is an approach to find out the price of delivered energy at a specific place by calculating and accounting the energy prices and transmission congestion [17]. By using this method, market clearing price (MCP) is calculated for various locations, which called nodes, on an electrical system. So, it is also called 'nodal pricing'.

[Locational Marginal Pricing] = [Marginal Cost of Generation] + [Marginal Cost of Losses] + [Marginal Cost of Transmission Congestion]

Expression of Market clearing price at bus 'i' can be stated as:

$$\lambda_i = \lambda_{Ref} - L_i \cdot \lambda_{Ref} - \sum_j \left(\mu_j \cdot SF_{ji}\right) \tag{3}$$

Where, 'λ_{Ref}' is marginal cost at reference bus, 'L_i' is marginal loss factor at bus 'i', 'μ_j' is shadow price of constraints 'j' and 'SF_{ji}' is shift factor for real load at bus 'i'.

3. Objective Function

Let, an electrical system having 'N_b' number of buses, 'N_l' number of loads and 'NG' number of generators. The objective function of the proposed approach is to maximize the revenue of the PSH plant and maximize the profit of the hybrid plant with considering the actual & predicted wind speed data, grid frequency and energy level of PSH plant. For calculating the profit of the system; revenue cost, deficit charge rate, surplus charge rate, imbalance cost and investment cost of wind power have been considered. The first objective of this work is to maximization of profit of the hybrid power plant. The expression of the profit is as follows:

$$\text{Maximize } P(t) = TR(t) + IC(t) - TG(t) \tag{4}$$

Where, P(t) is profit, TR(t) is total revenue, IC(t) is imbalance cost and TG(t) is total generation cost of wind-PSH hybrid power plant at time 't'.

$$TR(t) = R_{Thermal}(t) + R_{PSH}(t) \tag{5}$$

$$R_{Thermal}(t) = \sum_{i=1}^{NG} P_G(i,t) \cdot \lambda_{mrkt}(i,t) \tag{6}$$

$$R_{PSH}(t) = \left(R_{PSP}(t) + R_{wind}(t) - R_{loss}(t)\right) \tag{7}$$

Here, $R_{Thermal}(t)$ and $R_{PSH}(t)$ are the revenue of thermal and PSH plant respectively. $P_G(i,t)$ is the power generation of the i-th generator at time 't'. $\lambda_{mrkt}(t)$ is MCP at instant 't'. $R_{wind}(t)$ and $R_{loss}(t)$ are revenue of wind plant and loss in revenue. In this paper we have taken equation (7) as the second objective function, i.e. maximization of revenue of PSH plant. Where,

$$R_{PSP}(t) = R_{gen}(t) - R_{pump}(t) \tag{8}$$

$$R_{gen}(t) = P_g(t) \cdot \lambda_{mrkt}(t) \tag{9}$$

$$R_{pump}(t) = Pw_{pump}(t) \cdot \lambda_{wind} + Pg_{pump}(t) \cdot \lambda_{mrkt}(t) \tag{10}$$

$$R_{wind}(t) = Pw_{mrkt}(t) \cdot \lambda_{mrkt}(t) \tag{11}$$

$$R_{loss}(t) = \omega \cdot \lambda_{mrkt}(t) \cdot \left\{P_d(t) - Pw_{mrkt}(t) - P_g(t)\right\} \tag{12}$$

Here, $R_{PSP}(t)$, $R_{gen}(t)$ and $R_{pump}(t)$ are total revenue, reverue at generation mode and revenue at pumping mode of PSH plant respectively in \$/hr. $P_g(t)$ is power generated when PSH is in generating mode. $Pw_{pump}(t)$ is power for pumping of PSH supplied from wind and $Pg_{pump}(t)$ is power for pumping of PSH purchased from grid at market prices. λ_{wind} is the wind generation cost in \$/MW. $Pw_{mrkt}(t)$ is total power from wind supplied to grid in MW. ω is penalty factor. $P_d(t)$ is total power scheduled to be supplied at instant 't' from Wind–PSH plant in MW.

Depending on the predicted wind speed, the wind output power is calculate and this output power is committed in a day-ahead market scheme. The actual wind data will be mostly different from the predicted data so this difference in power is utilized by the PSH for its operation, such that the difference in power is compensated. But the difference between the actual and predicted wind speed, can produce imbalance cost. The expression of the imbalance cost, deficit charge rate and surplus charge rate are stated as follows-

$$IC(t) = \sum_{i=1}^{NG} \left(SCR(t) + DCR(t) \cdot \left(\frac{P_p(i,t)}{P_a(i,t)} \right)^2 \right) \cdot \left(P_a(i,t) - P_p(i,t)\right) \tag{13}$$

$$DCR(t) = (1+\beta) \cdot \lambda_{mrkt}(i,t), SCR(t) = 0 \quad \text{if } P_p(i,t) > P_a(i,t) \tag{14}$$

$$SCR(t) = (1-\beta) \cdot \lambda_{mrkt}(i,t), DCR(t) = 0 \quad \text{if } P_p(i,t) < P_a(i,t) \tag{15}$$

$$SCR(t) = DCR(t) = 0 \quad \text{if } P_p(i,t) = P_a(i,t) \tag{16}$$

$$TG(t) = GC(t) + WGC(t) \tag{17}$$

$$GC(t) = \sum_{i=1}^{NG} \left(a_i + b_i \cdot P_a(i,t) + c_i \cdot P_a^2(i,t)\right) \tag{18}$$

Here, SCR(t) and DCR(t) are surplus and deficit charge rate at time 't'. $P_a(i,t)$, $P_p(i,t)$ are generated power at i-th generation bus at time 't' with actual and predicted wind speed respectively. β is imbalance cost co-efficient (Assume β=0.9 for this work). GC(t), WGC(t) are generated cost of thermal power and wind generation cost at time 't'. a_i, b_i and c_i are generator price co-efficient.

3.1. Constraints for PSH Plant Operation

$$P_p(t) = Pw_{pump}(t) + Pg_{pump}(t) \tag{19}$$

$$P_p^{min} \le P_p(t) \le P_p^{max} \tag{20}$$

$$P_g^{min} \le P_g(t) \le P_g^{max} \tag{21}$$

$$E_{|v|}(t+1) = E_{|v|}(t) + \left\{\left(P_p(t) \cdot \eta_p\right) - \left(P_g(t) / \eta_g\right)\right\} \tag{22}$$

$$E_{|v|}^{min} \le E_{|v|}(t) \le E_{|v|}^{max} \tag{23}$$

Where, $P_p(t)$ is total pumping load of PSH. P_p^{min}, P_p^{max}, P_g^{min}, P_g^{max} are minimum & maximum pumping and generation limit of PSH plant respectively. $E_{|v|}$ is energy level of PSH plant in MWhr. η_p, η_g are efficiency of PSH plant when in pumping mode and generating mode. $E_{|v|}^{min}$, $E_{|v|}^{max}$ are minimum and maximum PSH energy level.

3.2. Constraints for Solving Optimal Power Flow

$$\sum_{i=1}^{NG} P_{Gi} + WP - P_{loss} - P_L = 0 \tag{24}$$

$$P_{loss} = \sum_{J=1}^{N_l} G_J \left\{ |V_i|^2 + |V_j|^2 - 2|V_i||V_j| \cos(\delta_i - \delta_j) \right\} \tag{25}$$

$$P_i - \sum_{k=1}^{N_b} |V_i V_k Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) = 0 \tag{26}$$

$$Q_i + \sum_{k=1}^{N_b} |V_i V_k Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) = 0 \tag{27}$$

$$V_i^{min} \le V_i \le V_i^{max} \qquad i=1,2,3... N_b \tag{28}$$

$$\phi_i^{min} \le \phi_i \le \phi_i^{max} \qquad i=1,2,3... N_b \tag{29}$$

$$TL_l \le TL_l^{max} \qquad l=1,2,3... N_l \tag{30}$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \qquad i=1,2,3... N_b \tag{31}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \qquad i=1,2,3... N_b \tag{32}$$

Where, P_{Gi} is power generation at i-th generation unit, WP is generated wind power. P_{loss}, P_L are transmission loss and power demand. G_J is line conductance of the line connected between buses 'i' and 'j'. $|V_i|$, $|V_j|$, V_k are voltage magnitude of bus 'i', bus 'j' and bus 'k'. δ_i, δ_j are voltage angle of bus 'i' and bus 'j'. P_i, Q_i are real and reactive power injected into the system at bus number 'i'. Y_{ik}, θ_{ik} are magnitude and angle of element of i-th row and k-th column of bus admittance matrix. V_i^{min}, V_i^{max}, ϕ_i^{min}, ϕ_i^{max}, P_{Gi}^{min}, P_{Gi}^{max}, Q_{Gi}^{min}, Q_{Gi}^{max} are lower and upper limit of voltage, plase angle, real power and reactive power of bus 'i'. TL_l, TL_l^{max} are actual and maximum line flow limit of line 'l'.

4. Proposed Strategy

A strategy has been developed to minimize the effect of imbalance cost and maximize the revenue & profit of a wind-thermal-pumped storage hybrid power plant by optimal scheduling of energy level of the PSH plant. MIPS has been used for solving the optimal power flow problem. Actual & predicted wind speed data, grid frequency for 24 hours have been assumed for checking the effectiveness of the proposed approach. Based on the assumed wind speed, the output power is calculated by the graph shown in Fig. 1. Depending on the difference between predicted & actual wind power, grid frequency and energy level of PSH; operation of PSH is decided i.e. whether the PSH should work in pumping mode or generating mode or be idle. Then this operating condition is passed as the limits of the PSH units and an OPF simulation is done whose main aim is to minimize the fuel cost. Since wind and PSH generation has least generation cost, therefore more profit can be achieved after optimal scheduling of generation. Revenue and profit of the wind-thermal-PSH hybrid plant is found which is based on the output power from the OPF simulation.

Reference [8] gives an operating strategy for PSH plant with a frequency based pricing environment i.e. the schedule of operation of PSH is determined by checking the frequency. But in the current work, a strategy which provides an additional new constraint of energy level of PSH (E_{opt} and E_{low}) along with system frequency in order to determine the optimal operation schedule of PSH.

The operation of the PSH using the presented strategy depends on the following parameters:

- Predicted or committed wind power and actual wind power.
- Frequency at every instant.
- Current energy level of the PSH plant.

Fig. 3 gives the flow chart of the presented operating strategy of PSH plant where, P_{wact}, P_{wpre} are power generated from actual and predicted wind speed; P_{pumin}, P_{pumax} are minimum and maximum limit of power when PSH is operated as pump; P_{gmin}, P_{gmax} are minimum and maximum limit of power when PSH is operated as generator in MW; $P_{fromwind}$ is power supplied to grid from wind in MW; E_p is input power for pumping of PSH plant and E_g is generated power in generation mode of PSH plant. From the Fig. 3 it can be seen that, there are 11 operating states presents in the operating strategy and all cover broadly under the following 6 cases:

Case 1: $P_{wact} \geq P_{wpre}$ and $f > 50$ Hz

In this case, the actual wind speed is greater than the predicted one and the frequency of grid is also greater than 50 Hz, this means power generated from wind is more than committed power to give and there is excess power in grid as frequency is high. Since the supply of power is more than demand, then the power will be available at comparatively lesser price. To make use of this low price and to reduce the excess power in the grid so as to bring down frequency to 50 Hz, PSH is operated as a pump with pumping level up to the maximum limit as stated in operating state 1.

Case 2: $P_{wact} \geq P_{wpre}$ and 49.7 Hz $\leq f \leq$ 50 Hz

Similar to Case 1, here also actual wind power is greater than the predicted value but the frequency is between 50Hz and 49.7 Hz. For this scenario PSH operates in operating state 2. The committed power *or* predicted power is supplied to power grid and the excess power which is the difference between actual and predicted wind power, is used to operate the PSH as a pump.

Case 3: $P_{wact} \geq P_{wpre}$ and $f <$ 49.7 Hz

Here the actual power from wind is again greater than predicted value but the frequency is below 49.7 Hz. which indicate that there is shortage of power in grid. For this case there are three operating states, depending on the energy level of PSH units. For this operating strategy the usable energy level between the maximum and minimum PSH storage level (E_{max} and E_{min}) have been further break into two more levels E_{opt} and E_{low}. When the energy level of PSH is below E_{low}, it can be treated as a warning that the usage of PSH as generator should be done in only emergency conditions may be to prevent a grid collapse due to reduction in frequency etc. When the energy level of PSH is below E_{opt} means there is moderate amount of water in PSH and if energy level of PSH is above E_{opt} then there is excess water than needed and generation can be done at any instant so as to maximize the profit of wind-thermal-PSH hybrid system.

In this case, energy level of PSH is checked after checking the frequency, if the energy level of PSH is lesser than E_{low} then the PSH will be idle and the actual power generated from wind will be delivered to grid for improving the frequency, as in operating state 3. If the energy level is greater than E_{low} but lesser than E_{opt} then, since the grid is in need of power the market price of power will be high; so in order to maximize revenue of wind-thermal-PSH plant, the PSH is operated in generating mode with generation limited to half of maximum generation limit of the PSH plant shown in state 4.

In another case, if energy level of PSH is greater than E_{opt}, it means that there is more than sufficient reservoir storage in PSH and so since the market price of power is high, then PSH is used as a generator with its maximum generating capacity as in operating state 5.

Case 4: $P_{wact} < P_{wpre}$ and $f > 50$ Hz

In this case, predicted wind power is greater than actual power and the frequency is greater than 50 Hz. Even though the supply to the grid is lesser than the predicted value; there is excess power in the grid as frequency is greater than 50 Hz, so there is no point for operating the PSH as generator to supply the predicted power as this will only increase the frequency further. In this scenario, PSH is operated as pump for increasing the load on the system so as to maintain the grid frequency at its normal value of 50 Hz. Focusing on energy level of PSH, two operating states have been devised with two distinct pumping limits. Pumping limit of PSH is set to its

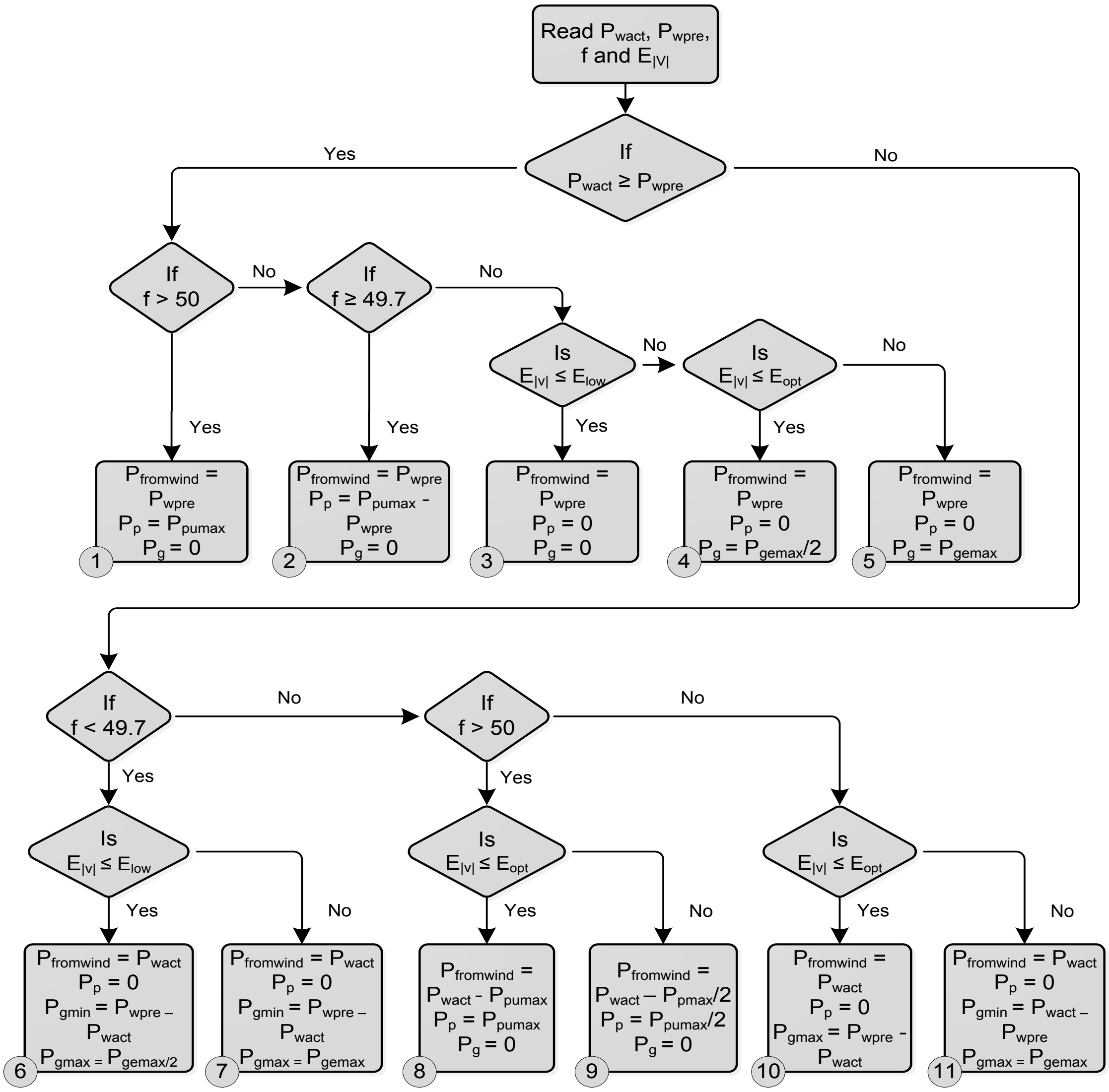

Fig. 3. Flow-Chart of The Proposed Approach

maximum value (shown in state 8), when energy level is lesser than E_{opt} and otherwise pumping will be at half of the maximum pumping limit as in operating state 9. The power for pumping operation will be given from wind rather than purchasing power from grid for both cases as power from wind sources will be cheaper. After the power utilized for pumping, the remaining power will be sold to the grid.

Case 5: $P_{wact} < P_{wpre}$ and 49.7 Hz ≤ f ≤ 50 Hz

In this case also, predicted power is greater than actual and frequency is between 49.7 Hz and 50 Hz. Here PSH operates in generating mode in order to supply the difference between the committed power and actual power. Like state 8, focusing on the energy level of PSH, there are two operating states have been proposed. If the energy level of PSH is lesser than E_{opt} then PSH acts as generator and supplying the difference between predicted and actual power (shown in operating state 10), otherwise the PSH acts as a generator with setting its maximum value at PSH maximum generation and minimum value is set to the difference between actual and predicted power of pump-storage plant as shown in operating state 11.

Case 6: $P_{wact} < P_{wpre}$ and f < 49.7 Hz

Here, the predicted power is greater than actual and the frequency is lesser than 49.7 Hz. Since the frequency is less, there is large power demand in the system but hybrid plant is not fulfilling the demand, then PSH plant operates as generator. When the current energy level is lesser than E_{low}, then the PSH acts as generator to supply at least the difference between predicted and actual power (as shown in operating state 6). If energy level is greater than E_{low} then the PSH will set the minimum power generation level at the difference between actual and predicted value whereas maximum power generation level is set to the maximum generation capacity of the PSH (as shown in operating state 7).

5. Implementation of the Proposed Strategy

The proposed logic has been implemented in modified IEEE 30 bus system. The OPF problem has been solved by MIPS for obtaining the desired objectives by considering the various power systems constrains. A set of 20 wind turbines with a maximum capacity of 3.5 MW each, have been considered in this work and placed at bus no. 5; so maximum power output of wind plant is 70 MW at rated speed. The investment cost of the wind power plant is taken from [17]. It is assumed that the maximum energy storage capacity of PSH plant is 80 MWhr and this plant is connected to bus no. 13. The operation of PSH as generator or pump is decided as per the proposed logic of Fig. 3 depends on the actual & predicted wind power, frequency of the grid and energy level of PSH plant. Initial PSH level is assumed as 41 MWhr. The E_{opt} value is assumed at 40 MWhr, E_{low} at 20 MWhr and E_{min} at 10 MWhr. By using the logic of Fig. 3; details about the power from wind sold to grid, pumping or generation limits of PSH are received.

The OPF gives minimum generating cost considering the several power system constraints. The other constraints of energy level with PSH generation & pumping limits are also set before running the OPF. Since the OPF always finds out minimum cost by generation re-scheduling and as the cost of generation are comparatively lower for wind and PSH as compared to other thermal plants in the system, the wind and PSH will be completely utilized in this competitive environment. The revenue of the wind-thermal-PSH hybrid system is then calculated based on the scheduled generating pattern. The results of proposed logic have been compared with the existing logic given in paper [8]. But the algorithm used in [8] is based on Artificial Bee Colony (ABC); hence the logic of ref [8] is again programmed using the MIPS algorithm to compare our result with the existing logic.

6. Application of Proposed Strategy

Modified IEEE 30 bus system has been considered to investigate the effectiveness of the proposed approach. Modified IEEE 30 bus system has 6 generators, 41 transmission lines and 19 loads. Bus no. 1 has been considered as reference bus and reference MVA limit is set to 100 MVA. All system data including bus data, branch data, generator data and offer price co-efficient data have been taken from [18,19].

At first actual and predicted wind speed data of a selected place has been considered for a day-ahead market. Fig. 4 and Table 8 show the actual and predicted wind speed data, which has been taken as the input for checking and analyzing the proposed approach. Due to the uncertain nature of wind speed in real case, the variable wind speed was chosen for every hour.

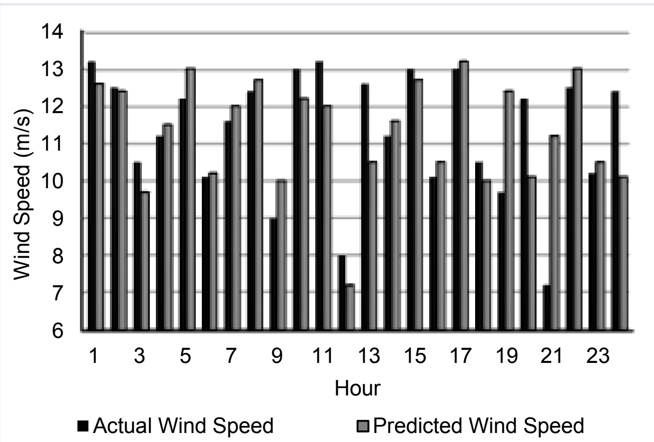

Fig. 4. Actual and Predicted Wind Speed Data for a Day

Grid frequency has also been chosen randomly (shown in Fig. 5 and Table 8) for operating the PSH plants and try to obtain the best results. From the Fig. 5, it can be seen that, the grid frequency is below 50 Hz in maximum hours which is not desirable for maintaining the system security. By using the proposed approach, it is tried to maintain the grid frequency and to reduce the chances for grid failure or blackouts of power system.

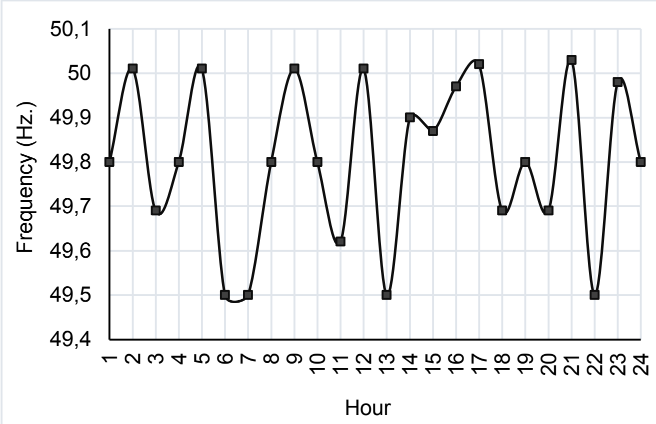

Fig. 5. Grid Frequency of a System for a Day

The profit of an electrical system at an instant time mainly depends on the system revenue and generation costs. The revenue of a power system is determined by the power generation capacity of every generator and market clearing price (Calculated using Equation 6) of the buses where generators are connected. Here, it is considered that the maximization of profit is an objective function in presence of imbalance cost. At first wind generator are placed at bus no. 5 of modified IEEE 30 bus system. After placement of wind generator, wind speed has varied as per the data taken for examine the approach, and calculate the imbalance cost, revenue and profit of the wind integrated thermal power station by solving the optimal power flow and get maximum profit by the generator re-scheduling. Table 1 shows the effect of imbalance cost on system profit. The '–ve' imbalance cost indicates the penalty imposed on GENCOS for deficit power supply and '+ve' imbalance cost indicates the reward provided to GENCOS for surplus power supply. It can be concluded from the Table 1 and Fig. 4 that, profit is maximum when imbalance cost is minimum, specifically when difference between the actual and predicted wind speed is minimum.

Now, proposed hybrid PSH plant strategy has been applied to maximize the profit, minimize the effect of imbalance cost and maintain the grid frequency. As per proposed approach (shown in Fig. 3), the operation mode of PSH has changed in every hours for fulfilling the system requirement, to maximize the profit and revenue. Generation scheduling takes very important role in the OPF problem. Table 2 shows the comparative study of PSH plant revenue, hybrid plant revenue, profit, market clearing price and new energy level of the system after applying the proposed logic. From the table it is also clear that, in maximum hours the energy levels of PSH plant have varied between the E_{min} and E_{opt}, hence maximum profit and revenue have been achieved up to maximum hours and wind power has utilized more for hybrid operation of wind-thermal-PSH plant.

Table 1. Imbalance Cost and Profit of Wind Integrated Thermal Power Systems

Hour	Imbalance Cost ($/Hr.)	Revenue Cost ($/Hr.)	Profit ($/Hr.)	Hour	Imbalance Cost ($/Hr.)	Revenue Cost ($/Hr.)	Profit ($/Hr.)	Hour	Imbalance Cost ($/Hr.)	Revenue Cost ($/Hr.)	Profit ($/Hr.)
1	-378.02	15097.64	3964.22	9	33.32	15692.51	3698.33	17	6.33	15126.04	4318.05
2	-61.04	15197.98	4174.54	10	-512.71	15126.04	3799.01	18	-321.42	15481.23	3595.01
3	-525.69	15481.23	3390.73	11	-790.08	15097.64	3552.17	19	88.67	15593.43	3871.71
4	9.75	15381.98	4039.66	12	-540.63	15832.26	2950.39	20	-1489.88	15240.56	2698.96
5	25.60	15240.56	4214.44	13	-1484.56	15183.49	2766.23	21	135.19	15943.23	3483.11
6	3.31	15538.02	3854.05	14	12.95	15381.98	4042.85	22	15.96	15197.98	4251.54
7	12.91	15325.9	4107.36	15	-185.56	15126.04	4126.15	23	9.85	15523.61	3876.87
8	9.57	15211.71	4229.17	16	13.16	15538.02	3863.90	24	-1652.47	15211.71	2567.14

Table 2. Comparative Study of Revenue and Profit of the System (Proposed Logic)

Hour	Revenue of PSH Plant ($/Hr.) (A)	Revenue of Thermal Plant ($/Hr.) (B)	Total Revenue of Hybrid Plant ($/Hr.) (C=A+B)	Generation Cost of Thermal Power ($/Hr.) (D)	Wind Power Cost ($/Hr.) (E)	Total Cost ($/Hr.) (F=D+E)	Profit ($/Hr.) (G=C-F)	Energy Level (MWHr.)	MCP ($/MWHr.)
1	2934.9	15451.1	18386.0	13151.8	223.1	13374.9	5011.1	43.94	54.77
2	2507.3	15984	18491.3	13524.4	207.8	13732.2	4758.9	52.34	55.47
3	3756.8	15257.2	19014.0	12647.2	164.0	12811.2	6202.8	41.23	54.65
4	3087.1	15270.3	18357.4	12834.7	179.3	13014.0	5343.0	35.67	54.73
5	1258.6	16265.2	17523.8	13706.1	201.2	13907.3	3616.5	44.07	56.47
6	3356.7	15313.8	18670.5	12683.1	155.3	12838.4	5832.1	32.96	54.86
7	3680.1	15101.8	18781.9	12551.9	188.1	12740.0	6041.9	21.85	54.07
8	3088.3	15172.9	18261.2	12892.5	205.6	13098.1	5163.1	19.91	54.40
9	161.1	16728.7	16889.8	14044.2	131.2	14175.4	2714.4	28.31	58.17
10	2780.4	15599.4	18379.8	13250.4	218.7	13469.1	4910.7	32.23	55.09
11	4109.4	14986	19095.4	12665.8	223.1	12888.9	6206.5	26.67	53.70
12	960.3	16741.3	17701.6	14053.9	109.3	14163.2	3538.4	35.07	58.22
13	4233.1	15071.4	19304.5	12714.8	210	12924.8	6379.7	29.52	54.01
14	2776.6	15329.8	18106.4	12968.4	179.3	13147.7	4958.7	26.92	54.97
15	3024.6	15302.1	18326.7	13048.4	218.7	13267.1	5059.6	28.39	54.56
16	2454.7	15485.6	17940.3	13069.7	155.3	13225.0	4715.3	25.8	55.55
17	1699.2	16147.4	17846.6	13628.4	218.7	13847.1	3999.5	34.2	56.05
18	3143.5	15369.2	18512.7	12897.6	164.0	13061.6	5451.1	28.64	55.10
19	2407.1	15370	17777.1	12719.7	146.5	12866.2	4910.9	17.53	55.07
20	3615.6	15240.6	18856.2	12997.1	201.2	13198.3	5657.9	17.53	54.67
21	-1492.5	16989.3	15496.8	14253.9	91.8	14345.7	1151.1	25.93	59.17
22	3891.9	14973.4	18865.3	12477.5	207.8	12685.3	6180.0	14.82	53.61
23	2454.6	15484.8	17939.4	13089.9	157.5	13247.4	4692.0	12.88	55.55
24	2339.5	16235.4	18574.9	13686.4	205.6	13892.0	4682.9	21.28	56.36

Fig. 6 shows the maximum operating range of power for pumping mode and generation mode of the pump-hydro storage system after implementation of the proposed strategy. From the Fig. 6 it is seen that the range of power is zero at 20th hour, it means the PSH plant is in idle condition at that hour.

In a power system, generator offer price coefficients are fixed for all generators. Solution of the optimal power flow gives minimum generation cost by completing the generation re-scheduling for a thermal power plant. Fig. 7 shows the comparison of generation capacity for all generators in 24 hours interval after applying the proposed scheduling logic in hybrid power plant.

Revenue of an electrical system mainly depends on power generation and market clearing price (MCP). Fig. 8 shows the variation of MCP for all generator bus during 24 hours interval after implementing proposed logic in the wind integrated PSH plant in the fully deregulated environment. From Fig. 8 it is clear that, MCP is varied for every hour and for every generation buses due to the optimal generation re-scheduling. At 21st hour, the MCP is maximum for all generator buses, therefore at that hour the maximum revenue of thermal plant (shown in Table 2) can be achieved.

Comparison of Results

For comparing the result of proposed logic with existing logic of Reference [8], both the logic is implemented simultaneously in a common power system. Table 3 shows the comparative study of PSH plant revenue, hybrid plant revenue, profit, market clearing price and new energy level of the system after applying the existing logic [8]. There are no energy levels present near the minimum energy level in the existing approach [8]. From the table, it is clear that, the new energy level is nearer to the E_{max} in maximum hours. In the existing logic, more focus has given on the storage of PSH plant than system profit. The investment cost of wind power is 3.75 $/MWhr. [17]. By using this data, wind power cost is determined for several wind power capacities and the same is used for calculating the overall profit of the system.

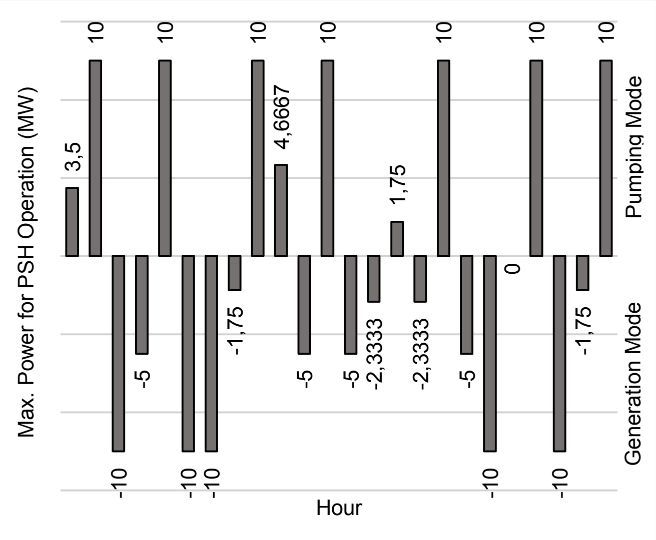

Fig. 6. Operating Range of Power for PSH Plant (Proposed Logic)

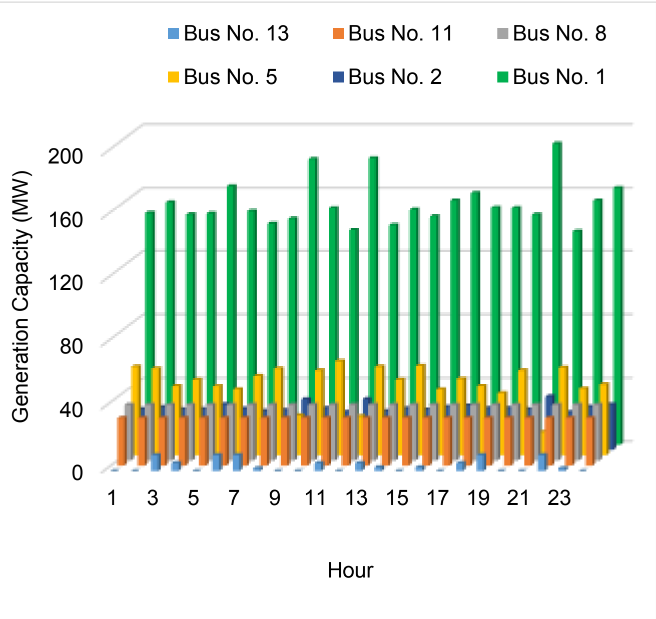

Fig. 7. Generation Scheduling of Modified IEEE 30 Bus System after Applying the Proposed Logic

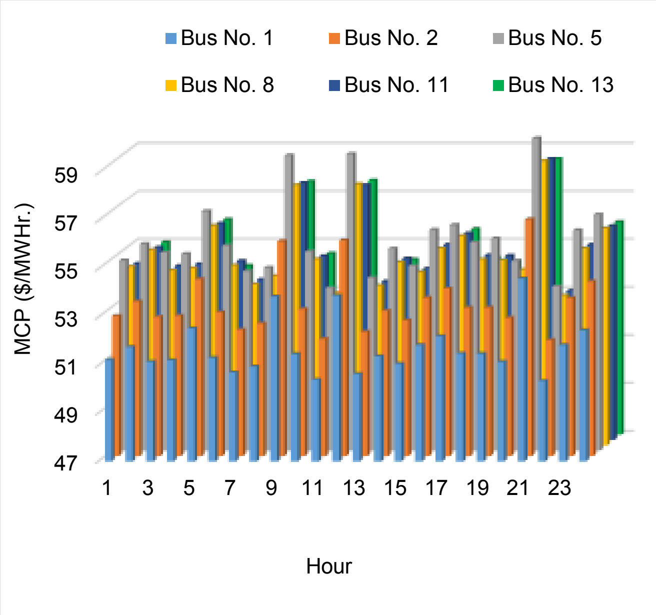

Fig. 8. Variation of Market Clearing Price of All Generator Buses after Applying the Proposed Logic

Fig. 9 and Fig. 10 shows the comparative study of the revenue of PSH plant and wind-thermal integrated PSH hybrid power plant respectively. From Fig. 9 it is clear that, proposed logic gives more economical results as compared to the existing logic in maximum hours. Overall revenue of PSH plant for that particular day is 62228.8 $ for proposed logic whereas, existing logic gives 56805.9 $ revenue for that day. So, it can be concluded that proposed logic is more superior than existing logic. In the 21st hour, revenue is negative for both logics; at that case thermal plant takes the initiative for maintaining and improving the profit of the hybrid plant.

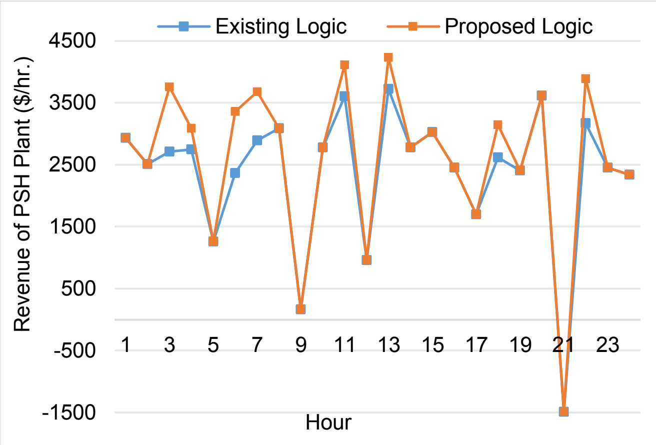

Fig. 9. Comparison of Revenue of PSH Plant for 24 hours

Also proposed logic gives better result than the existing logic [8], in terms of the revenue of wind-thermal-PSH hybrid plant. Overall revenue for the hybrid plant using existing logic is 432851.5 $/day whereas, revenue is 437099.5 $/day by using proposed logic. From the Fig. 10 it can be seen that, at 21st hour revenue is minimum for both the logic, because at that time PSH plant gives the minimum revenue.

Table 3. Comparative Study for Revenue and Profit of the System (Using Existing Logic [8])

Hour	Revenue of PSH Plant ($/Hr.) (A)	Revenue of Thermal Plant ($/Hr.) (B)	Total Revenue of Hybrid Plant ($/Hr.) (C=A+B)	Generation Cost of Thermal Power ($/Hr.) (D)	Wind Power Cost ($/Hr.) (E)	Total Cost ($/Hr.) (F=D+E)	Profit ($/Hr.) (G=C-F)	Energy Level (MWHr.)	MCP ($/MWHr.)
1	2934.9	15451.1	18386	13151.8	223.1	13374.9	5011.1	43.94	54.7794
2	2507.3	15984	18491.3	13524.5	207.8	13732.3	4759	52.34	55.4718
3	2713.3	15481.1	18194.4	13150.7	164.1	13314.8	4879.6	52.34	55.5571
4	2747.4	15342.9	18090.3	12997.8	179.4	13177.2	4913.1	50.396	55.0327
5	1258.6	16265.2	17523.8	13706.2	201.3	13907.5	3616.3	58.796	56.4741
6	2365	15525.2	17890.2	13158.8	155.3	13314.1	4576.1	58.147	55.714
7	2891.2	15273.5	18164.7	12932.8	188.1	13120.9	5043.8	55.555	54.7716
8	3088.3	15172.9	18261.2	12892.6	205.6	13098.2	5163	53.61	54.4088
9	161.1	16728.7	16889.8	14044.3	131.3	14175.6	2714.2	62.01	58.1743
10	2780.4	15599.4	18379.8	13250.4	218.7	13469.1	4910.7	65.93	55.0929
11	3603.9	15097.8	18701.7	12912.3	223.1	13135.4	5566.3	65.93	54.1527
12	960.3	16741.3	17701.6	14053.9	109.4	14163.3	3538.3	74.33	58.2204
13	3725.6	15183.5	18909.1	12962.7	210	13172.7	5736.4	74.33	54.4632
14	2776.6	15329.8	18106.4	12968.4	179.4	13147.8	4958.6	71.737	54.9799
15	3024.7	15302.1	18326.8	13048.5	218.7	13267.2	5059.6	73.207	54.5694
16	2454.7	15485.6	17940.3	13069.7	155.3	13225	4715.3	70.615	55.5552
17	1699.2	16147.4	17846.6	13628.4	218.7	13847.1	3999.5	79.015	56.054
18	2616.1	15481.1	18097.2	13150.7	164.1	13314.8	4782.4	79.015	55.5571
19	2407	15370	17777	12719.7	146.6	12866.3	4910.7	67.904	55.0707
20	3615.6	15240.6	18856.2	12997.1	201.3	13198.4	5657.8	67.904	54.6707
21	-1492.5	16989.3	15496.8	14254	91.9	14345.9	1150.9	76.304	59.1719
22	3173.1	15132.9	18306	12826.2	207.8	13034	5272	73.063	54.2517
23	2454.6	15484.8	17939.4	13090	157.5	13247.5	4691.9	71.119	55.5558
24	2339.5	16235.4	18574.9	13686.5	205.6	13892.1	4682.8	79.519	56.3688

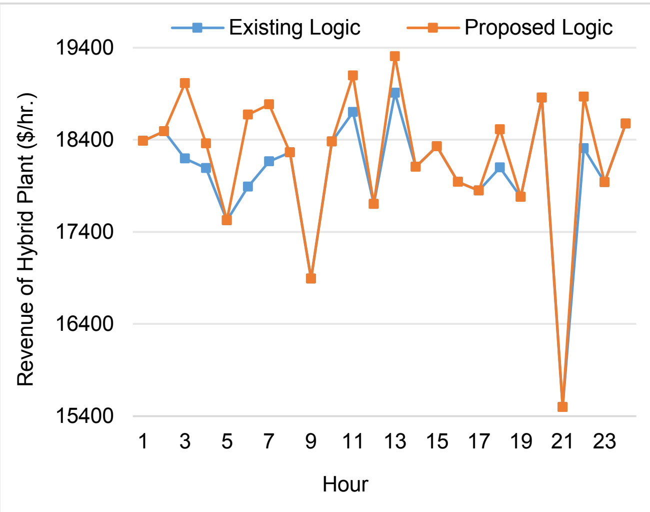

Fig. 10. Comparison of Revenue of Wind-PSH Hybrid Plant

Profit is the combination of revenue and generation cost. If revenue is greater than the generation cost, then profit has come, otherwise loss is occurred. Fig. 11 shows the comparative analysis of the existing logic [8] and proposed logic, for maximizing the profit of the wind-thermal-PSH hybrid plant. It is clear from the Figure that after using proposed logic, profit is maximized more during maximum time intervals as compared with the existing logic [8].

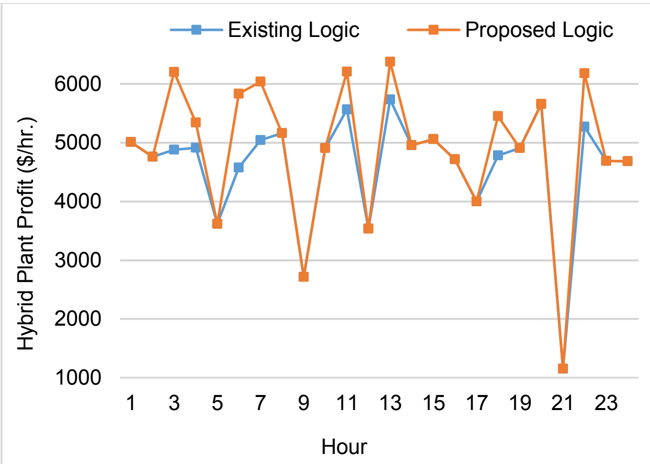

Fig. 11. Comparison of Profit of Wind-PSH Hybrid Plant

The main strategy has been proposed in this paper regarding the optimal scheduling of energy level of a PSH plant. A comparative study has been done for checking the effectiveness of the proposed approach (shown in Fig. 12). From the Figure it has shown that, energy level is in higher value in every hour when existing logic has applied. In proposed approach, the first priority is given to maintain the grid frequency by changing the mode of operation of PSH plant. And then tried to maintain the energy level of PSH plant is to near about E_{opt}, for maximizing the profit.

Table 4. Profit Comparison for Hybrid Plant for 24 Hour (Existing Logic [8] and Proposed Logic)

Hour	Profit without Storage ($/hr.)	Profit with Existing Logic ($/hr.) [8]	Profit with Proposed logic ($/hr.)	Hour	Profit without Storage ($/hr.)	Profit with Existing Logic ($/hr.) [8]	Profit with Proposed logic ($/hr.)	Hour	Profit without Storage ($/hr.)	Profit with Existing Logic ($/hr.) [8]	Profit with Proposed logic ($/hr.)
1	3964.22	5011.09	5011.09	9	3698.33	2714.24	2714.24	17	4318.05	3999.41	3999.41
2	4174.54	4758.96	4758.96	10	3799.01	4910.60	4910.60	18	3595.01	4782.39	5450.96
3	3390.73	4879.61	6202.71	11	3552.17	5566.26	6206.40	19	3871.71	4910.75	4910.75
4	4039.66	4913.13	5343.27	12	2950.39	3538.32	3538.32	20	2698.96	5657.86	5657.86
5	4214.44	3616.34	3616.34	13	2766.23	5736.38	6379.74	21	3483.11	1150.95	1150.95
6	3854.05	4576.07	5832.03	14	4042.85	4958.58	4958.58	22	4251.54	5271.99	6179.96
7	4107.36	5043.77	6041.78	15	4126.15	5059.53	5059.53	23	3876.87	4691.96	4691.96
8	4229.17	5163.01	5163.01	16	3863.90	4715.27	4715.27	24	2567.14	4682.79	4682.79

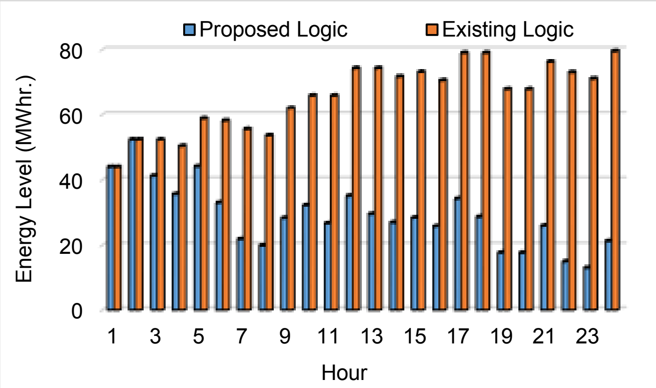

Fig. 12. Comparison of Energy Level of PSH Plant.

The main objective of this paper is to maximize the profit of wind-thermal-PSH hybrid plant. Table 4 and Fig. 13 shows the comparative study of the profit of the hybrid power plant with considering the three cases- profit without storage, profit with existing logic [8] and profit with proposed logic. In the case of 'profit without storage', no energy store has been used, so at that condition less profit will came.

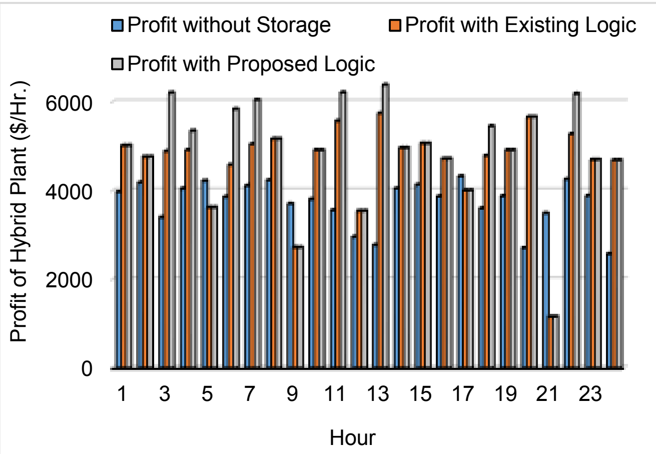

Fig. 13. Profit Comparison for Hybrid Plant for 24 Hours

From the Fig. 13 it is concluded that for every hour proposed logic gives maximum profit with minimizing the effect of imbalance cost. Only in 21st hour, profit is minimized after placement of storage system due to the 'negative revenue' or 'loss' occurring from the PSH plant.

For checking the elasticity of the proposed approach, the system load is varied and PSH plant revenue is calculated. In this work, the total system load is differ as per the load scaling factor (shown in Table 6) for the modified IEEE 30 bus system and comparison has been done between existing logic [8] and proposed logic. For every case the better results come after using the proposed approach (shown in Table 5). So, it can be concluded that proposed approach will be working in any system conditions.

Table 5. Revenue Comparison for Different Load Factor Over a Year for PSH Plant ($/Day)

Month	Proposed Logic	Existing Logic [8]	Month	Proposed Logic	Existing Logic [8]
Jan.	45415.89	41218.51	July	60296.03	55021.55
Feb.	32993.83	30769.27	Aug.	62202.84	56774.39
Mar.	27863.59	25964.35	Sept.	61185.07	55838.32
Apr.	27165.87	25275.81	Oct.	55729.25	50877.24
May	38671.92	35252.02	Nov.	41195.91	31597.68
June	53759.25	49073.54	Dec.	37754.30	27410.19

7. Conclusion

An efficient operating strategy has been proposed in this paper to maximize the profit of wind-thermal-PSH hybrid system for a day-ahead electricity market considering frequency as well as energy level of PSH plant. It is to be noted that the proposed strategy of PSH plant here is different from the conventional PSH operation. In conventional usage the PSH is used to provide peak shaving during peak demand time but here it is utilized in order to compensate for the uncertainties of wind power so as to meet its committed generation pattern. Here, PSH is scheduled to operate not only to compensate the difference in power between the predicted and actual but also to maximize the profit of the hybrid system. The results of the proposed approach are compared with the existing logic in ref [8]. The comparison is done only among two operating strategies using MIPS for solving the OPF problem. From the results, it is clear that the proposed logic gives better results for all cases. Simulations have been done on hourly basis and the loads at different buses are also varied for every hour. The results also indicate that the reservoir limits are utilized in a much better way by the presented method and so the revenue obtained is also better.

Appendix:

Table 6. Monthly Load Scaling Factor (LF)

Month	LF	Month	LF	Month	LF
Jan.	0.598937	May	0.512616	Sept.	0.969455
Feb.	0.497343	June	0.752988	Oct.	0.808101
March	0.435590	July	0.942231	Nov.	0.530544
April	0.434262	August	1	Dec.	0.486056

Table 7. Generator Cost Co-efficient & Active Power Limit

Bus	a	b	c	Pg_{min}	Pg_{max}	Bus	a	b	c	Pg_{min}	Pg_{max}
1	0.0384	40	100	50	200	8	0.01	40	110	10	35
2	0.25	40	124	20	80	11	0.01	40	0	10	30
5	0	40	0	0	0	13	0	4	0	0	0

Table 8. Input Data (AWS & PWS in m/s, f in Hz.)

Hr.	AWS	PWS	f	Hr.	AWS	PWS	f
1	13.2	12.6	49.8	13	12.6	10.5	49.5
2	12.5	12.4	50.01	14	11.2	11.6	49.9
3	10.5	9.7	49.69	15	13	12.7	49.87
4	11.2	11.5	49.8	16	10.1	10.5	49.97
5	12.2	13	50.01	17	13	13.2	50.02
6	10.1	10.2	49.5	18	10.5	10	49.69
7	11.6	12	49.5	19	9.7	12.4	49.8
8	12.4	12.7	49.8	20	12.2	10.1	49.69
9	9	10	50.01	21	7.2	11.2	50.03
10	13	12.2	49.8	22	12.5	13	49.5
11	13.2	12	49.62	23	10.2	10.5	49.98
12	8	7.2	50.01	24	12.4	10.1	49.8

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