GAME THEORY BASED SCHEDULING OF WIND AND PSP SYSTEM

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Abstract

The power produced by wind energy is non-dispatchable as well as uncertain resulting in market imbalances due to the difference between actual and scheduled generation. A mixed integer type problem with game theory based min-max approach has been used to reduce these uncertainties. To provide the balance between the demand and generation, flexible operation of pumped storage plant (PSP) is used with the wind system. The main objective of the problem is to provide the stable operation of wind-PSP system with different level of uncertainties risk under the day ahead market. In this study, different type of PSP units have been considered to demonstrate the advantage of variable speed type PSP unit in the wind-PSP operation. It has been found that the risk was reduced by 40% for using variable speed type PSP unit as compared to fixed speed unit. The developed model can be useful in decision making process for using wind PSP system.

Keywords: Wind-PSP generation; optimization problem; Min-Max approach, Wind power; Energy storage

1. Introduction

Wind energy is mostly intermittent and non-dispatchable renewable energy source. Generating companies provide various control schemes to reduce the fluctuation in availability of the wind energy system in the power market. Wind energy system can be integrated with the dispatchable energy sources like hydro, thermal, PSP etc. for increasing the benefits of wind system. Various researchers (Contaxis and Kabouris 1991; Dokopoulos et al. 1996; Chen 2008; Mahor et al. 2009; Nema et al. 2009) studied the integration of wind system with various dispatchable energy sources to improve the overall operational reliability and efficiency of the combined operation.

Integration of wind and energy storage device is necessary to utilize the full potential benefits and reducing the impact of uncertainty of the wind energy in day-ahead market. Yao et al. (2009), Ming-Shun et al. (2009) and Daim et al. (2011) used the various energy storage devices such as battery storage and flywheels etc., for minimizing the impact of wind energy. Tanabe et al. (2008) developed a forecasting scheduling model to use the battery as an energy storage device in order to reduce the effect of wind data uncertainty in the integrated network. Daneshi et al. (2010) considered compressed air energy storage (CAES) to store electricity generated by wind system. For the large size of wind system, PSP is found one of the economically viable and technically mature alternative for energy storage (Daim et al. 2011).

Form the past studies, it has been seen that the uncertainty in the wind data always affect the planning process of wind-PSP system. In the deregulated system, there are several sources of uncertainty like market demand, market prices and the power injected by generating system. For dealing with different source of uncertainties, game theory based model has been developed by various researchers in the past. Game theory is defined as a decision making technique, to analyze the different decision making problem of conflicting issues. In the recent years, many researchers used the game theory-based approaches to analyze the natural behavior of deregulated market (Kannan et al. 2010, Miglivacca et al. 2006, Ceppi et al. 2010 and Song et al. 2002).

In this study, game theory-based Min-Max optimization method has been used to minimize the uncertainty of the Wind System by providing the stable operation of the Pumped storage plant. Two types of uncertainties have been considered in this study:

1.1 Wind Data Uncertainty: To analyze the uncertainty in the wind energy resource, electrical output of wind system is forecasted and utilized by day-ahead market and for that it is required to study the wind frequency distribution characteristics. To predict the electricity generation by wind turbines for the day ahead scheduling, some of the forecasting techniques reviewed in this paper. An Artificial Neural Network (ANN) based forecasting techniques used by Jie et al. (2011) to predict the uncertainty in the wind system output. Pearson, Rayleigh and Weibull models are usually applied to fit the distribution of wind speed frequency (Al-Abbadi et al. 2009; Ruigang et al. 2011; Atawa 2011; Khathod et al 2010). In the present study, Weibull distribution technique is used to fit the six different scenario of wind system based on the speed as shown in fig 1.

$$V_1 = V_{\min} + \Delta V \tag{1}$$

$$V_i = V_{i-1} + \Delta V \qquad \text{where } V_i = \{V_2, V_3 ....V_n\} \tag{2}$$

where,

$$\Delta V = \frac{V_{\max} - V_{\min}}{n} \tag{3}$$

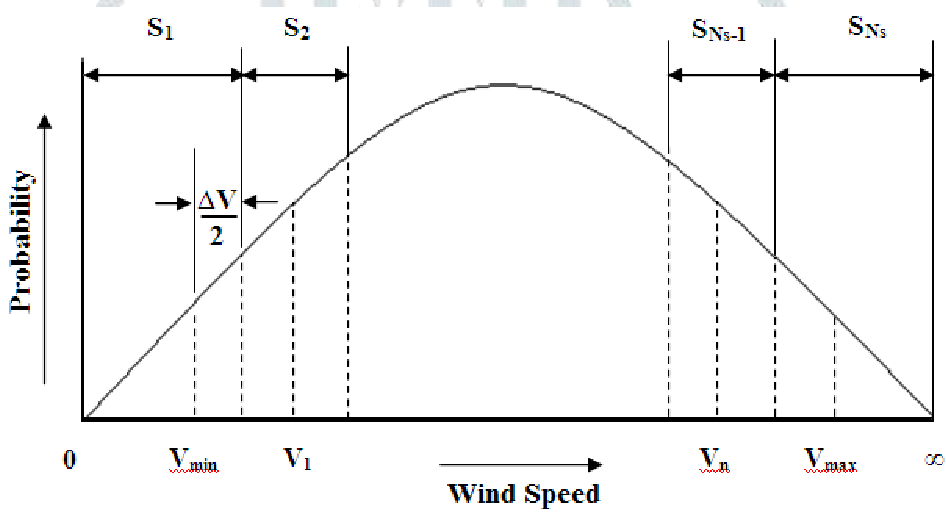

Fig. 1: Wind Speed probability distribution curve

$$s = \begin{cases} 0 \rightarrow V_{\min} + \dfrac{\Delta V}{2} & for \quad i = 1 \\ V_i - \dfrac{\Delta V}{2} \rightarrow V_i + \dfrac{\Delta V}{2} & for \quad 1 < i < Ns \\ V_{\max} - \dfrac{\Delta V}{2} \rightarrow \infty & for \quad i = Ns \end{cases} \tag{4}$$

$$f(V) = ba^{-b} V^{b-1} e^{-\left(\frac{V}{a}\right)^b} \tag{5}$$

$$F(V) = \int_0^{\infty} ba^{-b} V^{b-1} e^{-\left(\frac{V}{a}\right)^b} dt \quad = \quad 1 - e^{-\left(\frac{V}{a}\right)^b} \tag{6}$$

Where, Eq (5) and (6) are used to calculate the PDF for the six different scenarios for the model as shown in Fig. 2.

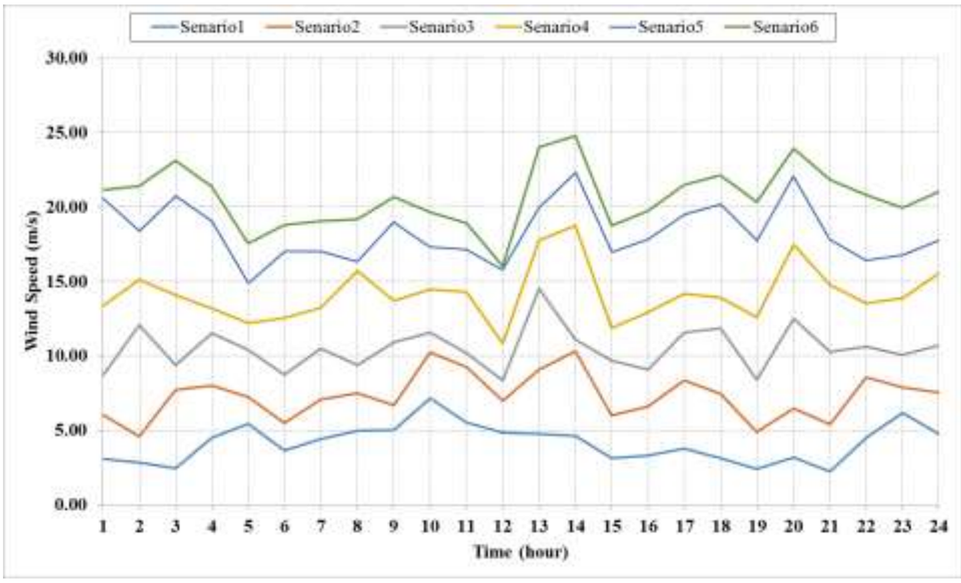

Fig. 2: Wind Speed for different scenarios

In Eq. (7) $P^{s}_{wind}(\mathrm{t})$ represents the actual value of wind generation at time *t*, and consists of fixed planned value $\bar{P}_{wind}(\mathrm{t})$ and variable or uncertain value of generation $\Delta P_{wind}(\mathrm{t})$

$$P^{s}_{wind}(\mathrm{t}) = \bar{P}_{wind}(\mathrm{t}) + \Delta P_{wind}(\mathrm{t}) \tag{7}$$

1.2 Uncertainty in market demand: A typical uncertainty in the market demand is shown in Fig. 3 and considered in the form of deterministic variable as represented by the minimum and maximum interval given in Eq. (8).

$$Pd_{\min} \le Pd(\mathrm{t}) \le Pd_{\max} \tag{8}$$

Where, the market demand Pd is the deterministic variable representing the market demand uncertainty. $Pd_{\min}$ and $Pd_{\max}$ are the minimum and maximum demand limits across the market respectively.

The uncertainty in market demand may also be written as Eq. (9):

$$Pd(\mathrm{t}) = \bar{P}d(\mathrm{t}) + \Delta Pd(\mathrm{t}) \tag{9}$$

where, $\bar{P}d(\mathrm{t})$ is the planned value of market demand and $\Delta Pd(\mathrm{t})$ is the demand variation across the market. These types of uncertainties are difficult to model as both the uncertain parameters do not have known probabilistic distribution. The uncertainty is expressed in the form of variation of parameters that will be modified in a certain magnitude affecting the generation capacity with time. Due to this fact, two feasible scenarios were considered in the model viz. the nominal scenario and the worst-case scenario.

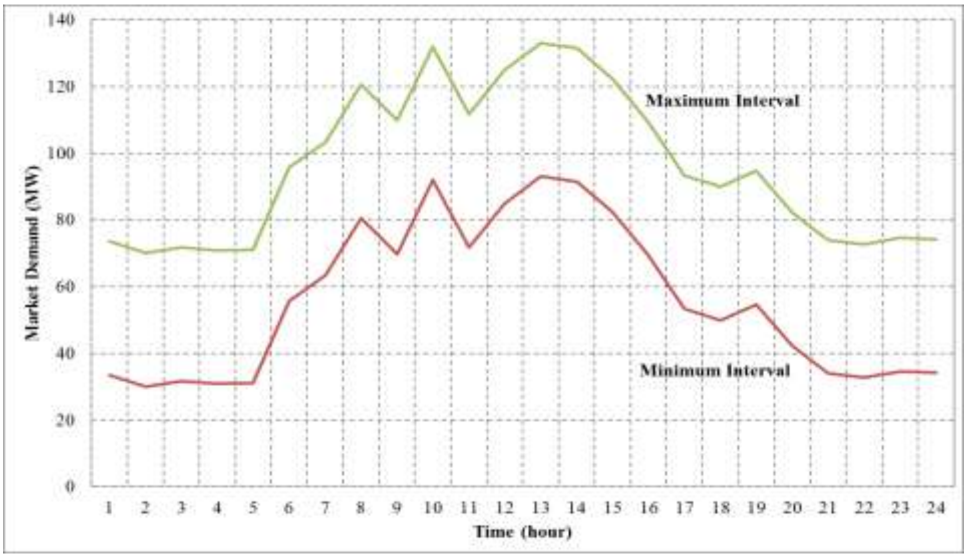

Fig. 3: Market demand

2. Problem Formulation

In this study, a game theory based techniques "Min-Max optimization" has been used to provide the Wind-PSP operation under any type of wind uncertainty. For this approach, scheduling of the Wind-PSP system has been done for two scenarios i.e. Nominal-case scenario and Worst-case scenario. Two types of PSP operation, fixed speed operation and variable speed operation have been considered for both of these cases.

Two models are used to analyze the problem. First model is the optimization model to schedule the generation bids in day-ahead market. The objective of this optimization problem is to minimize the imbalance cost occurred during wind-PSP operation. Second model is a Min-Max model, used to reduce the imbalance cost or risk caused by the uncertain wind data.

2.1 Optimization model for wind and PSP system

To minimize the market imbalances, market operator imposes the penalties on the power producer for creating such power imbalances. These penalties cause the revenue loss across the Wind-PSP system, which is defined as the difference between the power supplied by the both wind and PSP system and the market demand given in the Eq. (10).

$$P_{loss}(t) = \bar{P}d(\mathrm{t}) - (Pw_{mkt}(t) + s(t) \times P_{gen}(t)) \qquad (10)$$

The objective of this function is to minimize the imbalance cost as given in the Eq. (11).

$$F_{\min} = \min_{P_{gen}} \sum_{t \in T} \left(I_{\cos t}(P_{gen}(t), \bar{P}_{wind}(t), \bar{P}d(\mathrm{t}) \right) \qquad (11)$$

where

$$I_{\cos t}(P_{gen}(t), \bar{P}_{wind}(t), \bar{P}d(\mathrm{t})) = P_{loss}(t) \times \lambda_{mkt} \qquad (12)$$

where, I_{cost} is defined as the product of total power imbalance P_{loss} and market price λ_{mkt} at t^{th} hour (given in Eq. 14). P_{gen} is the power generated by PSP system and Pw_{mkt} is the power supplied by wind farm to meet market demand during Wind-PSP operation. Objective function given in Eq. (11) is subjected to various constraints as given in Eq. (12) to Eq. (20).

$$P_{gen}^{\min} \le P_{gen}(t) \le P_{gen}^{\max} \qquad (13)$$

$$P_{loss}(t) \ge 0 \qquad (14)$$

$$Pp(t) = Pp_{\max} \qquad (\textit{for Case-I}) \qquad (15)$$

$$Pp_{\min} \le Pp(t) \le Pp_{\max} \qquad (\textit{for Case-II}) \qquad (16)$$

$$E(t+1) = E(t) - \Big(\big(P_{gen}(t) \times s(t) \big) / \eta_t - \big(Pp(t) \times sp(t) \big) \times \eta_p \Big) \times \Delta t \qquad (17)$$

$$E_{\min} \le E(t) \le E_{\max} \qquad (18)$$

$$0 \le \bar{P}_{wind}(t) - Pw_{mkt}(t) - P_p(t) \times sp(t) \qquad (19)$$

$$s(t) + sp(t) \le 1 \qquad (20)$$

2.2 Min-max optimization model

The objective of this Min-Max optimization model is to min-max the risk R to provide the best performance under the uncertain condition as given in Eq. (21). Risk $R(\bar{\mathrm{P}}_{gen}, P_{wind}^{s}, Pd)$ is caused by the uncertainty in wind data and the market demand. In this model, P_{wind}^{s} is the min-max value of non-controllable variable, where scenario, s represent the uncertainty across the wind system. P_{gen} as well as Pd are the min-max values of controllable variables. $\bar{P}_{gen}$ is the planned value of min-max model as determined from the model (2.1).

$$\min_{\bar{P}_{gen}} \max_{P^{s}_{wind}, Pd} R(\bar{P}_{gen}, P^{s}_{wind}, Pd) \tag{21}$$

where:

$$R(\bar{P}_{gen}, \tilde{P}^{s}_{wind}, \tilde{P}d) = \sum_{t \in T} \left(I_{\cos t}(\bar{P}_{gen}(t), P^{s}_{wind}(t), Pd(t)\right) - F_{min} \tag{22}$$

$$I_{\cos t}(\bar{P}_{gen}(t), P^{s}_{wind}(t), Pd(t)) = P_{loss}(t) \times \lambda_{mkt} \tag{23}$$

$$P_{loss}(t) = Pd(t) - P^{s}_{wind}(t) - (s(t) \times \bar{P}_{gen}(t)) \tag{24}$$

Optimal conditions for the controllable variables in min-max model have been resolved while satisfying the various constraints given in Eq. (15-22) and (27-28).

$$Pd_{min} \le \tilde{P}d(t) \le Pd_{max} \tag{25}$$

$$R(\hat{P}_{gen}, P^{-}_{wind}, Pd^{-}) = R(\hat{P}_{gen}, P^{+}_{wind}, Pd^{+}) \tag{26}$$

As shown in the Eq. (25), the market demand $Pd(t)$ is the deterministic variable representing the market demand uncertainty. where Pd_{min} and Pd_{max} are the minimum and maximum demand limits across the market respectively.

Optimal condition of the min-max approach has been derived from the game theory with convex function and given in the Eq. (26). Two feasible scenarios: *(a)* worst-case scenario $\left(P^{-}_{wind}, Pd^{-}\right)$, at which system uncertainty risk is at its maximum value and *(b)* the nominal scenario $\left(P^{+}_{wind}, Pd^{+}\right)$, where the system uncertainty risk is at minimum value, have been determined. In order to provide the min-max optimization, the value across the controllable variable would be selected in such a way that the risk across the both selected scenarios should be same as given in Eq. 26, where, $\hat{P}_{gen}(t)$ is the optimal value for the min-max approach, satisfying the optimality condition of min-max approach.

3 METHODOLOGY

In this study, Min-max model is considered as mixed integer type problem. KNITRO, an AMPL based solver is used to optimize the value of this problem. This problem has been solved under uncertain wind data and market demand. The methodology to solve the min-max problem is described as below:

i. Considered the uncertainty of wind data and market demand. Here, the uncertainty across the wind data has been forecasted in the form of scenarios and uncertainty across the market demand has been considered in the form of deterministic variable as shown in Fig 2 and 3 respectively.
ii. Optimized the deterministic optimal scheduling of wind-PSP using the planned value of wind and market demand as given in para 1 and calculated the minimum imbalance F_{min}.
iii. Maximized the risk as given in Eq. 23 for optimizing the value of P_d and P_{wind} and found the risk for the nominal $R(\hat{P}_{gen}, P^{+}_{wind}, Pd^{+})$ and worst-case $R(\hat{P}_{gen}, P^{-}_{wind}, Pd^{-})$ scenarios as described in the para 2.2.

iv. Minimized the risk as given in Eq. (23) for optimized value of P_{gen} while satisfying the optimality constraints along with other constraints defined in para 2.2.

v. After the min-max optimization, if the risk for both nominal and worst-case are equal then the planned value of $\hat{P}_{gen}$ would be found for the both nominal and worst case scenarios for wind-PSP system

4 Results and Discussions

In the min max approach, the wind power output has been forecasted for six different scenarios. 150 MW wind farm data taken from Alta wind energy center (Alta-I), located at California, USA consisting of 100 units of 1.5 MW wind turbines each has been considered for these cases. Two cases have been analyzed to prove the optimality of the solution. Under Case-I, the pumped unit is operated at its rated power during the pumping mode, whereas under Case-II, power varies by variable speed type pumping unit. The wind farm can supply the power either to the market or for the pumping operation. The details of the wind-PSP system have been given in Table 1 and 2. The rating of PSP units has been taken from Hiwasse Dam unit-2 (Hiwasse Dam unit-2, 1956). The switching time between generation and pumping is considered to be zero. For both the cases, the initial reservoir level is assumed to be equal to 600 MWh with maximum and minimum reservoir level as 1200 and 400 MWh respectively.

Table 1: Pumped Storage Plant Data

Mode of Operation	Efficiency %	Rated Power, MW	
		Maximum Limit	Minimum Limit
Generation Mode	88.3	59.65	0
Pumping Mode	90.0	76.06	46.00

Table 2: Reservoir Data

Reservoir Type	Reservoir Capacity, MWh			
	Maximum	Minimum	Initial	Final
Offline	1200	400	600	600

The combined operation of the wind-PSP system for both nominal and worst cases have been shown in Fig 4 and Fig 5, whereas the generation and pumping operation of PSP for the both cases (Case-I and Case-II) are shown as Fig. 6. From Fig. 4 and 5, it has been found that Wind-PSP system scheduled its output in such a way that it would satisfy the optimality constraints so that the risk during both nominal and worst-case scenario would become same. PSP unit efficiently reduced the market imbalance as well as balanced the risk during both the scenarios. For variable speed operation of PSP, Case-II is seen to be more successful as compared to Case-I to reduce the risk of the system for both the scenarios.

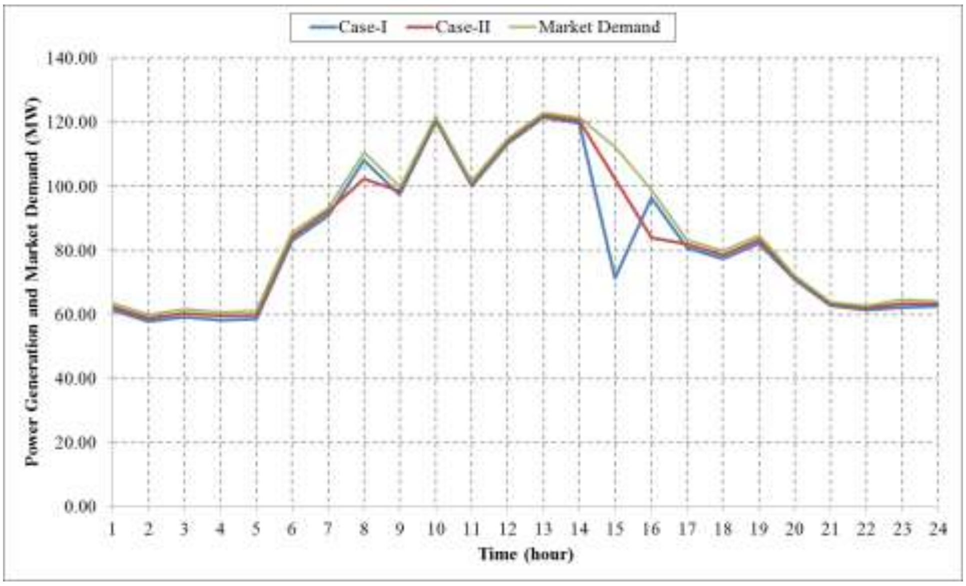

Fig. 4: Combined Wind-PSP Operation (Nominal-Case scenario)

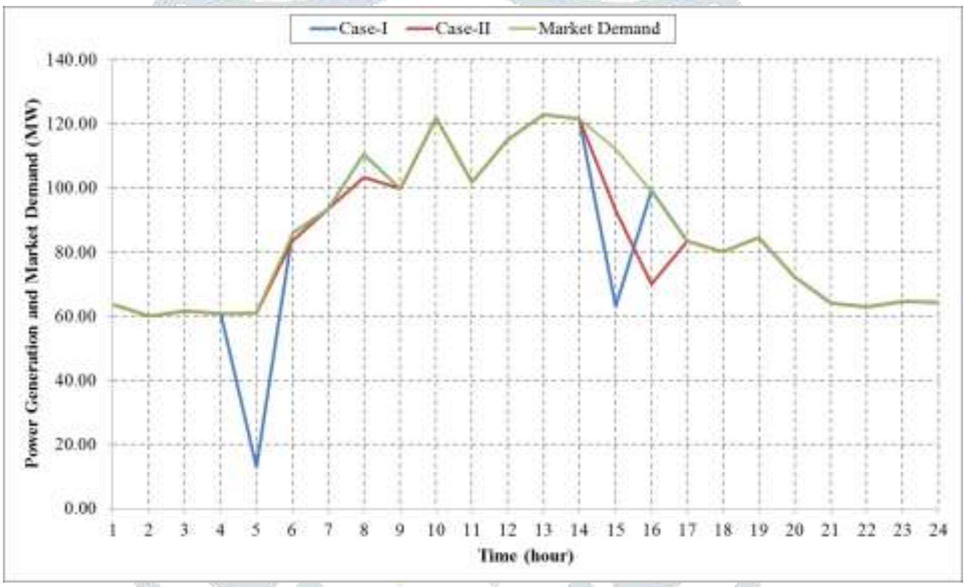

Fig. 5: Combined Wind-PSP Operation (Worst-Case scenario)

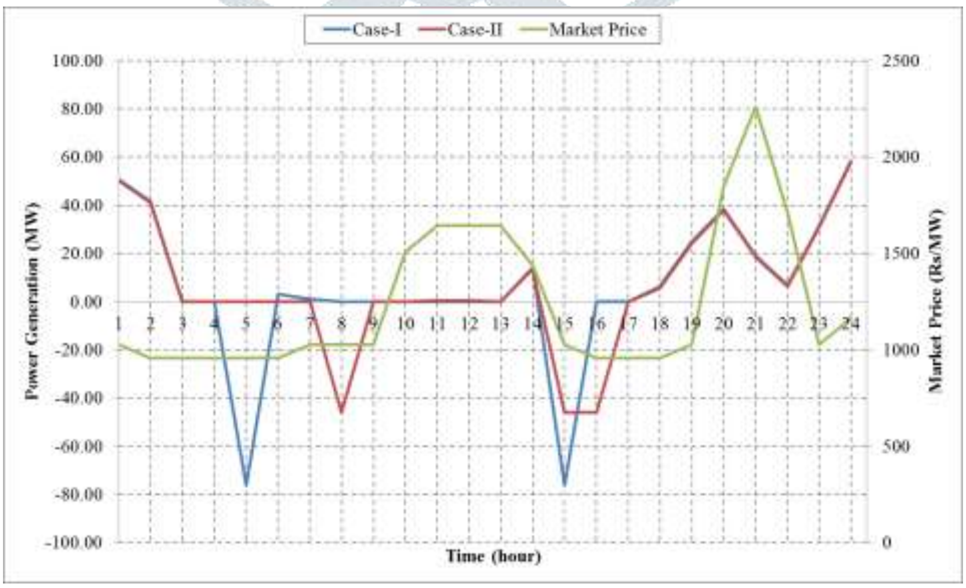

Fig. 6: Pumped Storage Plant Operation

Both wind and PSP supply the power to the market at the given market price. Table 3 and 4 show that during the low market price e.g. at 5 and 15 hours in Case-I and at hours 8, 15 and 16 in Case-II, the PSP tries to operate in pumping mode and store the energy in the upper reservoir. During the other hours of high market price, PSP operates in generating mode and uses stored energy from the upper reservoir. Case-II also provided more pumping as compared to Case-I due to variable operation. Table 5 represents the risk across the Wind-PSP system for the selected two scenarios (Nominal and Worst-case). From Table 5, it is seen that the use of variable pumping operation for Case-II can decrease the risk by 40 % for wind-PSP system by decreasing the imbalance costs as compared to Case-I, where the risk for the nominal and worst case scenario would remain same for both the cases.

Table 3: Optimal value for the variable (Case-I)

Variables	Description	Optimal Value (Case-I)							
1	Time, t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
2	$P_{gen}(t)$	50.66945	41.51	29.82	29.82	5.65	3.21	0.99	29.82
3	$s(t)$	1	1	0	0	0	1	1	0
4	$P_p(t)$	76.06	76.06	76.06	76.06	76.06	76.06	76.06	76.06
5	$sp(t)$	0	0	0	0	1	0	0	0
6	$Pw_{mkt}(t)$(nom. case)	10.74	16.24	59.17	58.32	58.71	79.99	89.91	108.12
7	$Pw_{mkt}(t)$(wrst. case)	12.88	18.53	61.7	60.85	12.86	82.53	92.3	110.6
8	$E(t)$	600	542.68	495.71	495.71	495.71	564.16	560.52	559.4
9	$Pd(t)$	63.55	60.05	61.7	60.9	61.1	85.75	93.3	110.6
10	$\lambda_{mkt}(t)$	1027.5	959	959	959	959	959	1027.5	1027.5
1	Time, t	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
2	$P_{gen}(t)$	29.83	29.83	0.59	0.612	29.82	14.06	4.74	29.82
3	$s(t)$	0	0	1	1	0	1	0	0
4	$P_p(t)$	76.06	76.06	76.06	76.06	76.06	76.06	76.06	76.06
5	$sp(t)$	0	0	0	0	0	0	1	0
6	$Pw_{mkt}(t)$(nom. case)	97.4	120.32	99.7	112.8	121.49	105.7	71.47	96.46
7	$Pw_{mkt}(t)$(wrst. case)	99.85	121.95	101.11	114.29	123	107.44	63.01	99.15
8	$E(t)$	559.41	559.41	559.41	558.74	558.05	558.05	542.14	610.59
9	$Pd(t)$	99.9	122	101.7	114.9	123	121.5	112.25	99.15
10	$\lambda_{mkt}(t)$	1027.5	1507	1644	1644	1644	1438.5	1027.5	959
1	Time, t	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
2	$P_{gen}(t)$	29.83	6.29	24.81	38.59	19.17	6.92	31.41	58.24
3	$s(t)$	0	1	1	1	1	1	1	1
4	$P_p(t)$	76.06	76.06	76.06	76.06	76.06	76.06	76.06	76.06
5	$sp(t)$	0	0	0	0	0	0	0	0
6	$Pw_{mkt}(t)$(nom. case)	80.77	71.09	57.42	32.36	43.74	54.44	30.93	4.46
7	$Pw_{mkt}(t)$(wrst. case)	83.35	73.66	59.84	33.61	44.83	55.82	33.24	5.96
8	$E(t)$	610.59	610.6	603.48	575.4	531.76	510.0	502.23	466.71
9	$Pd(t)$	83.35	79.95	84.65	72.2	64	62.75	64.65	64.2
10	$\lambda_{mkt}(t)$	959	959	1027.5	1849.5	2260.5	1712.5	1027.5	1164.5

From the Fig. 4 and 5, it is seen that by using the proposed min-max optimization technique, scheduling of the wind-PSP system is done by reducing the uncertainty involved in risk under the selected scenarios. The wind power is utilized efficiently by PSP and maintained the reliability of the system. However, the proposed optimization model has limitations in decision making. Consideration of constraint such as balance between initial as well as final levels of the upper reservoir for a PSP plant is necessary to make the model more practical. The effectiveness of the proposed approach can be further investigated by comparing with other existing methods or techniques such as Nash equilibrium, Taguchi technique and CVaR Methodology etc. The developed model can be helpful in decision-making process and can adapt more to the existing practical systems by addressing the limitations mentioned above.

Table 4: Optimal value for the variable (Case-II)

Variables	Description	Optimal Value (Case-II)							
1	Time, *t*	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
2	$P_{gen}(t)$	50.24	41.05	29.82	29.82	29.82	29.83	29.82	29.86
3	$s(t)$	1	1	0	0	0	0	0	0
4	$P_p(t)$	61.22	61.07	61.03	61.03	61.03	61.03	61.03	46
5	$sp(t)$	0	0	0	0	0	0	0	1
6	$Pw_{mkt}(t)$(nom. case)	12.26	17.84	60.47	59.62	59.87	84.51	92.13	102.47
7	$Pw_{mkt}(t)$(wrst. case)	13.31	19	61.7	60.85	61.1	83.3	93.3	103.3
8	$E(t)$	600	543.17	496.73	496.73	496.73	496.73	496.73	496.73
9	$Pd(t)$	63.55	60.05	61.7	60.9	61.1	85.75	93.3	110.6
10	$\lambda_{mkt}(t)$	1027.5	959	959	959	959	959	1027.5	1027.5
1	Time, *t*	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
2	$P_{gen}(t)$	0.08	0.08	29.82	29.82	29.82	13.51	29.99	29.76
3	$s(t)$	1	1	0	0	0	1	0	0
4	$P_p(t)$	61.01	61.01	61.03	61.03	61.03	64.4	46	46
5	$sp(t)$	0	0	0	0	0	0	1	1
6	$Pw_{mkt}(t)$(nom. case)	98.6	121.05	100.97	114.17	122.26	107.15	102.49	84.03
7	$Pw_{mkt}(t)$(wrst.. case)	99.77	121.87	101.7	114.9	123	107.99	93.07	70.02
8	$E(t)$	538.13	538.03	537.94	537.94	537.94	537.94	522.65	564.05
9	$Pd(t)$	99.9	122	101.7	114.9	123	121.5	112.25	99.15
10	$\lambda_{mkt}(t)$	1027.5	1507	1644	1644	1644	1438.5	1027.5	959
1	Time, *t*	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
2	$P_{gen}(t)$	29.82	5.61	24.23	38.01	18.58	6.33	30.79	57.96
3	$s(t)$	0	1	1	1	1	1	1	1
4	$P_p(t)$	61.03	63.37	61.18	61.68	61.15	75.63	61.08	61.1
5	$sp(t)$	0	0	0	0	0	0	0	0
6	$Pw_{mkt}(t)$(nom. case)	82.11	73.1	59.27	33.55	44.89	55.72	32.73	5.39
7	$Pw_{mkt}(t)$(wrst. case)	83.35	74.34	60.42	34.19	45.42	56.42	33.86	6.24
8	$E(t)$	605.45	605.45	599.1	571.68	528.68	507.66	500.49	465.66
9	$Pd(t)$	83.35	79.95	84.65	72.2	64	62.75	64.65	64.2
10	$\lambda_{mkt}(t)$	959	959	1027.5	1849.5	2260.5	1712.5	1027.5	1164.5

Table 5: Risk across Wind-PSP system (*Rs*)

Scenario	Case-I	Case-II
	Wind and fixed speed type PSP	Wind and variable speed type PSP
Nominal-Case	96856.26	57493.47
Worst-Case	96856.26	57493.47

5 Conclusions

In this study, it has been examined that wind penetration in the power market always effect the market operation. To reduce these impacts in the wind and PSP system a game theory based technique has been applied. Probabilistic forecasting based techniques has been used, which successfully forecast the system uncertainty under day ahead market. For successfully applying the game theory across the system, two scenarios known as worst and nominal scenarios have been selected based on their uncertainty level. From the results, it is concluded that with min-max optimization technique, scheduling of the wind-PSP system was successful for reducing the uncertainty involved in risk by decreasing the imbalance costs under the selected scenarios. Scheduling is done in such a way that the risk involved in operating wind-PSP system and would remain same for all the scenarios considered. By using this method, risk was reduced by 40% for operating variable speed unit as compared to fixed speed PSP unit. However, the proposed optimization model also has some limitations like consideration of constraint such as balance between initial as well as final levels of the upper reservoir for a PSP plant are necessary to make the developed model more practical. The effectiveness of the proposed approach can be further investigated by comparing with other existing methods or techniques such as Nash equilibrium, Taguchi technique and CVaR Methodology etc. The developed model can be considered helpful in decision-making process and can adapt more to the existing practical systems by addressing the limitations mentioned above.

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