SCHEDULING OF WIND-PSP GENERATION UNDER DAY-AHEAD MARKET

Ph.D. THESIS

by

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AUGUST, 2014

SCHEDULING OF WIND-PSP GENERATION UNDER DAY-AHEAD MARKET

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ALTERNATE HYDRO ENERGY CENTRE

by

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the thesis entitled "**SCHEDULING OF WIND-PSP GENERATION UNDER DAY-AHEAD MARKET**" in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from July, 2010 to August, 2014 under the supervision of Dr. Arun Kumar, Chair Professor (Renewable Energy) and Chief Scientific Officer and Dr. S.K. Singal, Principal Scientific Officer, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

(JAVED DHILLON)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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Date: August , 2014

ABSTRACT

The world today is facing major environmental challenge in meeting energy needs. Rising fossil fuel prices, oil insecurity, concerns about climate change and erratic weather patterns cast a shadow over the future use of coal, oil and other conventional sources of energy. Such concerns and increasing energy prices encouraged the search for cost competitive alternate sources of energy. Energy obtained from inexhaustible renewable sources like wind, solar and hydro is reliable, clean and will have long term benefits. Various countries including India have taken policy initiation for speedy development of renewable sources. During 2009-10 in India, wind energy has been found the fastest growing renewable energy and added the highest installed capacity among renewable energy sources compared to the other top four wind energy developing countries viz USA, Germany, China and Spain.

Despite the apparent advantages of wind power, it faces major challenges being variable and intermittent in nature. To limit the impact of the intermittence of wind power, water storage ability of the pumped storage plant combined with a wind power plant is called the wind-pumped storage plant (Wind-PSP). The main advantage of a wind and pumped storage plant is to complement energy by optimizing the available local wind and hydropower resources to ensure high levels of quality, reliability and performance of power supply with cost effective installation and operation.

Literature review reveals that earlier studies in this area have not considered the efficient bidding strategy for operating wind and variable speed type pumped storage unit to increase the profit in day-ahead or spot market. Very few studies considered wind data uncertainty in short term scheduling of wind-PSP to reduce market imbalance. No study has been reported for the management of the risk associated with wind and market uncertainty to provide stable operation of wind-PSP system under uncertain condition.

The objective of the present study is to provide the scheduling of wind-PSP system to increase the day-ahead market profit as well as reducing the market imbalance with limiting the active power output variations of wind energy resources by considering the needs of grid and stored energy available in PSP. For this short term scheduling problem stochastic approach has been applied to consider the effect of wind data uncertainty. This study determined and managed the uncertainty risk for the stable operation of the wind-PSP system. A min-max approach also has been provided with the objective to minimize the effect of uncertainty risk of wind-PSP system under the worst conditions.

In order to achieve above objectives, a 24 hours time frame has been considered in this study for the hourly scheduling of wind and pumped storage plant under day-ahead market, where both wind and pumped storage system are operated as a single entity, but not necessarily installed at the same or adjacent location. PSP considered in the study, consists of reversible turbine unit which can either generate electricity or pump the water as per requirement. Both the systems (wind and PSP) are connected with the grid. An optimal strategy is developed to efficiently utilize the power generated by wind and PSP as per the demand or bid received from the electricity market.

In order to achieve the above objective, a mixed integer type problem has been formulated for providing the scheduling of wind-PSP system. The optimal solution has been obtained by considering four cases. In the first case (Case-I), only wind farm has been considered to supply the power under the day-ahead market and attempted to increase the overall profit. In the second case (Case-II), the combined operation of wind-PSP system has been used, where the PSP operated at fixed speed during pumping mode. In the third case (Case-III), pumping is done at two different speeds, whereas in the fourth case (Case-IV) variable speed operation has been provided, which further reduced the market imbalances created by wind system.

Uncertainties in the electricity market always affect scheduling operation of wind-PSP system. These uncertainties are in the form of price, demand and generation. For the power generation entities or the market operator, these uncertainties are mostly unknown at the time of scheduling or bidding. In the present study, stochastic approach has been used to formulate the wind-PSP scheduling problem considering the wind system uncertainty as input data. Under this problem, an average sum of each individual solution set of uncertain input data weighted by their associated probability is considered in order to achieve a single solution. A probability based forecasting model has been used to forecast the uncertainty in the input data and computed the probability distribution function for the each set of input data. This solution has been found the best for all the individual solutions rather than solution from single set of input data. Three cases have been studied to check the optimality of the solution. In first two cases, wind-PSP system is considered to provide the scheduling under uncertain condition by operating the PSP in fixed and variable pumping modes, whereas third case provided the scheduling operation for grid connected wind-PSP to increase the overall profit under the deregulated environment.

As discussed above, probabilistic forecasting technique is used to predict the wind uncertainty, but in most of the cases, forecasting results were not very accurate and brought risks in the system. To manage these risks properly, an experimental design technique based on Taguchi method is employed to calculate and manage the uncertainty risk in this study. The proposed method utilized orthogonal array based structure, which is easy to implement and uses limited number of experiments thus demands less computational time. An adjustable speed type PSP unit has been considered, which effectively reduced the market imbalances occurred by uncertainties in wind generation and market demand.

Further, a game theory based Min-Max optimization method has been developed to reduce the effect of uncertainty during Wind-Pumped Storage System scheduling. The solution of this problem provided the best worst case performance of the system under uncertain condition. In the developed model, two feasible scenarios, the nominal scenario and the worst-case scenario were considered using the concepts of min-max optimization.

The uncertainty risk has been further reduced by providing the integrated operation with pumped storage plant (PSP).

The main aim of this research work was to provide the scheduling of wind-PSP system in order to increase the overall profit across wind-PSP system for day-ahead market. It has been found that in the wind and pumped storage scheduling, fixed speed type PSP units reduced the market imbalance by 60% and increased the overall profit by 19%. The profit was further improved to 31% by replacing the fixed pumped storage unit with a variable speed pumping unit. The operation of the pump unit in varying speed mode not only increased the total revenue but also decreased the market imbalance by 38% which otherwise would have caused the revenue loss during the combined operation. It is concluded that the utilization of wind energy has been increased from 1 to 4% by operating with grid system under uncertain condition. Thus grid connected wind-PSP system further improved the overall profit by 4%.

Taguchi method based model has been developed to optimize the wind-PSP operation under uncertain condition. This method reduced the operation risk of wind-PSP system under uncertain conditions by 64%. The major advantage of this approach is to design a wind-PSP system, which is able to withstand any level of risk and provide the stable performance under uncertain condition.

With min-max optimization technique, scheduling of the wind-PSP system was successful in 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 would remain same for all scenarios. By using this method risk was reduced by 20% for operating variable speed unit as compared to fixed speed PSP unit.

The developed Wind-PSP model can be considered as a significant tool in decision-making process for day-ahead market scheduling.

ACKNOWLEDGMENT

I express my deep and sincere gratitude to **Late. Prof. J. D. Sharma**, former chairman of Student Research Committee (AHEC) and Professor in Department of Electrical Engineering, Indian Institute of Technology Roorkee, for his love, affection, wide knowledge, logical way of thinking and personal guidance as key strength to accomplish this research work. His inspiring and priceless guidance is a key of success for me. I always remain grateful to Prof. for his continuous motherly love and support.

The author wishes to offer his profound and sincere gratitude to **Dr. Arun Kumar**, Chair Professor (renewable energy) and Chief Scientific Officer and **Dr. S. K. Singal**, Principal Scientific Officer, Alternate Hydro Energy Centre (AHEC), Indian Institute of Technology Roorkee, for their inspiring guidance, valuable suggestions and substantial encouragement throughout the course of this research work. Words would fail to record the invaluable help which the author was privileged to receive from them on numerous occasions.

I express my sincere thanks to Dr. R. P. Saini, Chairman, Centre Research Committee, Prof. D. K. Srivastav, Department of Hydrology (Chairman of Centre Research Committee upto June 2013), Dr. Ganesh Kumbhar of Electrical Engineering Department and Dr. Dheeraj K. Khatod of Alternate Hydro Energy Centre for being members student research committee for me for time to time reviewing the work and providing valuable suggestions.

The author owes his sincere gratitude to the faculty and staff of the Alternate hydro Energy Centre for the facilities and the cooperation received whenever needed.

The financial support received from Ministry of Human Resource and Development, Government of India, New Delhi is gratefully acknowledged.

The author wishes to record his sincere thanks and indebtedness to his colleagues Dr. Sachin Mishra, Dr. Siddharth Jain, Mr. Raj Kumar Viral, Mr. Mohit Bansal, Mr. V.S.V.K. Harish, Mr. Tabish Alam, Mr. Pushkar Tripathi, Mr. Neeraj Gupta and others, all of whom have rendered selfless help and support in numerous ways during the course of this study. Thanks are due to Mr. Deepak Kapil for the assisting in type setting of the thesis.

The author recognizes with warm appreciation the moral support and ever growing blessings of his parents, brothers, sister-in-laws and nephew.

Last but not the least, author wishes to thank numerous well wishers and friends who have contributed, directly or indirectly in compilation of work.

Above all author bestows himself Almighty God and fall short of words to express thanks for blessing, with an opportunity to carry the present work.

JAVED DHILLON

CONTENTS

CHAPTER	TITLE		PAGE NO.
CANDIDATE'S DECLARATION			
ABSTRACT			**i**
ACKNOWLEDGEMENT			**v**
CONTENTS			**vii**
LIST OF FIGURES			**xiii**
LIST OF TABLES			**xvii**
NOMENCLATURE			**xix**
CHAPTER 1	**INTRODUCTION**		**1**
	1.1	GENERAL	1
	1.2	WIND POWER	2
		1.2.1 Wind Power: Global Scenario	3
		1.2.2 Wind Power – Indian Scenario	4
		1.2.3 Wind Energy Applications	5
		1.2.4 Wind Power – Development Challenges and Opportunities	6
	1.3	ENERGY STORAGE SYSTEMS (ESSs)	7
		1.3.1 Applications of Energy Storage Technologies	7
		1.3.2 Energy Storage Technologies Classification	9
		1.3.3 Comparison of Various Energy Storage Technologies	9
	1.4	PUMP STORAGE SYSTEM (PSP)	12
	1.5	WIND-PSP SYSTEM	14
		1.5.1 Typical Arrangement of Wind-PSP System	15
	1.6	WIND-PSP CONCEPT	17

CHAPTER		TITLE	PAGE NO.
1.7		CHALLENGES AND OPPORTUNITIES FOR WIND-PSP DEVELOPMENT UNDER DEREGULATED MARKET	18
	1.7.1	Major Challenges to Wind-PSP Systems	19
	1.7.1.1	Wind Power Challenges	19
	1.7.1.2	Pumped Storage Development Challenges	20
	1.7.1.2.1	Environmental Issues for Storage Siting	20
	1.7.1.2.2	Regulatory Issues with deployment of Pumped Storage Plants	21
	1.7.1.2.3	Existing Market Rules and Impact on Energy Storage Value	21
	1.7.1.2.4	Restriction for Generation and Transmission	22
1.8		DEREGULATED MARKET	22
	1.8.1	Types of Deregulated Market	23
	1.8.1.1	Spot or Day Ahead Market	23
	1.8.1.2	Ancillary Services Market	24
	1.8.1.3	Real Time Market	24
1.9		WIND-PSP SCHEDULING UNDER DEREGULATED MARKET	25
1.10		LITERATURE REVIEW	26
	1.10.1	Energy storage systems for wind power operation	26
	1.10.2	Scheduling of Wind-PSP System	28
	1.10.3	Wind-PSP Under Deregulated Market	32
	1.10.4	Risk Management of Wind-PSP System	34
1.11		RESEARCH GAPS	35

CHAPTER	TITLE		PAGE NO.
	1.12	OBJECTIVES OF RESEARCH WORK	36
	1.13	AUTHOR'S CONTRIBUTION	36
	1.14	ORGANIZATION OF THE THESIS	37
CHAPTER 2	**WIND-PSP GENERATION SCHEDULING UNDER DAY-AHEAD MARKET**		**39**
	2.1	INTRODUCTION	39
	2.2	OPERATION OF WIND POWER PLANT	41
	2.3	OPERATION OF PUMPED STORAGE PLANT	42
	2.4	WIND-PSP SCHEDULING UNDER DAY AHEAD MARKET	43
		2.4.1 Objective Function	44
		2.4.2 Control Variables	45
		2.4.3 Constraints	45
		2.4.3.1 Energy Balance Constraints	45
		2.4.3.2 Pumping Constraint	47
		2.4.3.3 Imbalance Constraint	47
		2.4.3.4 Reservoir Limit	47
		2.4.3.5 Reservoir level	48
		2.4.3.6 Generation Limit	48
		2.4.3.7 Pumping Limit	48
		2.4.3.8 Switching Constraint	48
	2.5	SOLUTION TECHNIQUE	49
		2.5.1 Branch and Bound Method	49
		2.5.2 Branch and Bound Algorithm	50
	2.6	RESULTS AND DISCUSSIONS	51
CHAPTER 3	**WIND-PSP SCHEDULING CONSIDERING THE WIND UNCERTAINTY**		**59**
	3.1	INTROUCTION	59
	3.2	WIND SPEED FORECASTING MODEL	60
	3.3	WIND-PSP SCHEDULING MODEL	64

CHAPTER		TITLE		PAGE NO.
		CONSIDERING THE WIND UNCERTAINTY		
		3.3.1	Objective Function	65
		3.3.2	Control Variables	68
		3.3.3	Constraints	68
		3.3.3.1	Grid Pumping Limits	68
		3.3.3.2	Wind Power Constraint	69
		3.3.3.3	Pumping Constraint	69
		3.3.3.4	Imbalance Constraints	69
		3.3.3.5	Energy Balance Constraint	70
		3.3.3.6	Reservoir Limit	70
		3.3.3.7	Generation Limit	70
		3.3.3.8	Pumping Limit	71
		3.3.3.9	Switching Constraint	71
	3.4	METHODOLOGY		71
	3.5	RESULTS AND DISCUSSIONS		72
CHAPTER 4	**RISK MANAGEMENT OF WIND-PSP SYSTEM**			**81**
	4.1	INTRODUCTION		81
	4.2	WIND-PSP MODEL FOR RISK MANAGEMENT		83
		4.2.1	Objective Function	84
	4.3	TAGUCHI’S ORTHOGONAL ARRAY MODEL		84
	4.4	RESULTS AND DISCUSSIONS		88
CHAPTER 5	**GAME THEORY BASED SCHEDULING OF WIND AND PUMPED STORAGE SYSTEM**			**97**
	5.1	INTRODUCTION		97
	5.2	PROBLEM FORMULATION AND MODELS		100
		5.2.1	Optimization model for wind and PSP system	100
		5.2.1.1	Objective Function	100
		5.2.1.2	Constraints	101

CHAPTER	TITLE		PAGE NO.
	5.2.1.2.1	PSP generation limits	101
	5.2.1.2.2	Imbalance Constraint	101
	5.2.1.2.3	Pumping Power Constraint	101
	5.2.1.2.4	Energy storage equation	101
	5.2.1.2.5	Upper reservoir limits	102
	5.2.1.2.6	Wind power constraints	102
	5.2.1.3	Control Variable	102
	5.2.2	Min-max optimization model	103
	5.2.2.1	Objective Function	103
	5.2.2.1.1	Power demand uncertainty	103
	5.2.2.1.2	Wind power constraints	104
	5.2.2.2	Optimality condition of min-max approach	104
	5.3	METHODOLOGY	104
	5.4	RESULTS AND DISCUSSIONS	105
CHAPTER 6	**CONCLUSIONS AND RECOMMENDATIONS**		**109**
	6.1	CONCLUSIONS	109
	6.2	RECOMMENDATIONS	111
	6.3	FUTURE SCOPE	112
	REFERENCES		**113**
	LIST OF PUBLICATIONS		**135**

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE NO.
Fig.1.1	Global renewable energy consumption (%) at the end of 2013	2
Fig.1.2	Average annual growth rates of renewable energy capacity and biofuels production	3
Fig. 1.3	Global wind energy installed and projected capacity (GW)	4
Fig. 1.4	State wise wind installed capacity (MW) as on 31-01-2014	5
Fig. 1.5	Application, benefits and challenges of energy storage system along the electricity value chain	8
Fig. 1.6	Classification of ESSs as a function of investment costs per unit of power or unit of energy	10
Fig. 1.7	Pumped storage hydro power plant arrangement	13
Fig. 1.8	Integrating wind with pumped storage for shaping wind variability	15
Fig. 1.9	A typical arrangement of wind-PSP system	16
Fig. 2.1	Pumped Storage Plant Model	46
Fig. 2.2	Node based search tree	49
Fig. 2.3	Branch and bound flow chart	51
Fig. 2.4	Wind Farm System Operation (Case-I)	53
Fig. 2.5	Wind Farm and Pumped Storage Plant Operation (Case-II)	53
Fig. 2.6	Operation of Pumped Storage Plant (Case-II)	54
Fig. 2.7	Energy Storage Level in Upper Reservoir (Case-II)	54
Fig. 2.8	Wind Farm and Pumped Storage Plant Operation (Case-III)	55
Fig. 2.9	Operation of Pumped Storage Plant (Case-III)	56
Fig. 2.10	Energy Storage Level in Upper Reservoir (Case-III)	56
Fig. 2.11	Wind Farm and Pumped Storage Plant Operation (Case-	57

FIGURE NO.	TITLE	PAGE NO.
	IV)	
Fig. 2.12	Operation of Pumped Storage Plant (Case-IV)	57
Fig. 2.13	Energy Storage Level in Upper Reservoir (Case-IV)	58
Fig. 2.14	Profit and revenue loss comparison	58
Fig. 3.1	Wind Speed probability distribution curve	61
Fig. 3.2	Wind Speed data for different scenarios	62
Fig. 3.3	Power Output Vs Wind Speed	64
Fig. 3.4	Wind-pumped storage plant model	67
Fig. 3.5	Wind Farm and Pumped Storage Plant Operation (Case-I)	75
Fig. 3.6	Operation of Pumped Storage Plant (Case-I)	75
Fig. 3.7	Energy Storage Level in Upper Reservoir (Case-I)	76
Fig. 3.8	Wind Farm and Pumped Storage Plant Operation (Case-II)	77
Fig. 3.9	Operation of Pumped Storage Plant (Case-II)	77
Fig. 3.10	Energy Storage Level in Upper Reservoir (Case-II)	78
Fig. 3.11	Wind Farm and Pumped Storage Plant Operation (Case-III)	79
Fig. 3.12	Operation of Pumped Storage Plant (Case-III)	79
Fig. 3.13	Energy Storage Level in Upper Reservoir (Case-III)	80
Fig. 3.14	Comparison of profit and market imbalance under different cases	80
Fig. 4.1	Upper wind speed limits for six different scenarios	86
Fig. 4.2	Lower wind speed limits for six different scenarios	86
Fig. 4.3	Wind and pumped storage plant operation (Case-I)	89
Fig. 4.4	Operation of pumped storage plant (Case-I)	90
Fig. 4.5	Energy storage in upper reservoir (Case-I)	90
Fig. 4.6	Risk or profit loss across six different scenarios	92
Fig. 4.7	Wind and pumped storage plant operation (Case-II)	93
Fig. 4.8	Operation of pumped storage plant (Case-II)	94
Fig. 4.9	Energy storage in upper reservoir (Case-II)	94
Fig. 5.1	Market demand	99

FIGURE NO.	TITLE	PAGE NO.
Fig. 5.2	Combined Wind-PSP Operation	106
Fig. 5.3	Pumped Storage Plant Operation	106

LIST OF TABLES

TABLE NO.	TITLE	PAGE NO.
Table 1.1	Comparison of various ESS technologies	11
Table 2.1	Pumped Storage Plant Data	52
Table 2.2	Reservoir Data	52
Table 2.3	Result of Wind and Pumped Storage Plant Operation	52
Table 3.1	Weibull distribution scale and shape parameters	63
Table 3.2	Wind PSP System	73
Table 3.3	Market imbalances across each scenario	73
Table 3.4	Wind energy utilized by each scenario	73
Table 3.5	Total grid pumping by each scenario	74
Table 3.6	Total expected profit and market imbalance for all cases	74
Table 4.1	Orthogonal Array selector table	87
Table 4.2	Structure of $L_8(2)^6$ Orthogonal Array (OA)	87
Table 4.3	Test Response of OA	88
Table 4.4	Orthogonal Array with Test Result	91
Table 4.5	Risk or profit loss across each scenario	92
Table 4.6	Total expected profit for all cases	92
Table 4.7	Market imbalances across each scenario	95
Table 4.8	Wind energy utilization by each scenario	95
Table 5.1	Risk across Wind-PSP system (*Rs*)	107

ρ	Wind Density
Ω	Penalty Factor
$\pi(t,s)$	Probabilistic Factor at t_{th} time of s_{th} scenario
$\lambda_{mkt}(t)$	Market price at t_{th} time
$\lambda_{mkt}(t,s)$	Market price at t_{th} time of s_{th} scenario
λ_{wind}	Price paid by PSP for wind utilization for pumping
A	Area
a	Scale parameter for Weibull distribution
AMPL	A Mathematical Programming Language
ANN	Artificial Neural Network
APSO	Adaptive Particle Swarm Optimization
ARIMA	Auto Regressive Integrated Moving Average
Avg	Average value
b	Shape parameter for Weibull distribution
B	Variation limits
B&B	Branch and Bound Method
CA	California state of USA
CAES	Compressed Air Energy Storage
CDF	Cumulative Distribution Function
CLP	COIN-OR Linear Programming
Cp	Betz Constant
CUE	Cost of Unit Energy
CVaR	Conditional Value At Risk
dA	Variation in average value
DACP	Day-Ahead Commitment Process
DR	Demand Response
E(t)	Energy Stored in upper reservoir at t_{th} time
E(t,s)	Energy Stored in upper reservoir at t_{th} time at t_{th} time of s_{th} scenario

E_0	Initial energy level in upper reservoir
EA	Evolutionary Algorithm
EC	Electrochemical Capacitor
E_k	Kinetic Energy
$E(t)$	Energy stored in upper reservoir at t_{th} time
$E(t,s)$	Energy stored in upper reservoir at t_{th} time of s_{th} scenario
E_{max}	Maximum energy level in upper reservoir
E_{min}	Minimum energy level in upper reservoir
ERCOT	Electricity Reliability Council of Texas
ERG	Embedded Renewable Generation
ESS	Energy Storage System
E_T	Final energy level in upper reservoir
FERC	Federal Regulatory Energy Commission of USA
GA	Genetic Algorithm
GPAC	Global Variant Based Passive Congregation
GWEC	Global Wind Energy Council
h	Head, water level difference between upper and lower reservoir
H	High Value
HTT	Hilbert-Huang Transform
I_{cost}	Cost due to market Imbalance
IOHMM	Input Output Hidden Markov Model
IPM	Interior Point Method
IRM	Integrated Risk Management
ISO	Independent System Operator
L	Low Value
$L_h(B)^{Ns}$	Orthogonal Array with h_{th} experiments, Ns Scenarios and B_{th} *Variation*
LMP	Locational Marginal Pricing
LP	Linear Programming
LPSP	Loss of Power Supply Probability
m	Mass

MCP	Market Clearing Price
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NaS	Sodium-Sulfur
Ns	Total number of scenario
O&M	Operation and Maintenance
OA	Orthogonal Array
$\overline{Ph}$	Optimal value of PSP generation
$P_d(t)$	Market demand at t_{th} time
$P_d(t,s)$	Market demand at t_{th} time of s_{th} scenario
$\tilde{P}d(\mathrm{t})$	Uncertain market demand at t_{th} time
$\bar{P}d(\mathrm{t})$	Fixed planned value of market demand at t_{th} time
$\Delta\tilde{P}d(\mathrm{t})$	Variable or uncertain value of market demand at t_{th} time
Pd^{-}	Market demand at uncertainty risk is at maximum value
Pd^{+}	Market demand at uncertainty risk is at minimum value
$Pd_{\min}$	Minimum value or interval of market demand
$Pd_{\max}$	Maximum value or interval of market demand
PDF	Probability Density Function
P_e	Electrical Power generated by wind turbine
P_{gen}	Power Generated by PSP
$P_{gen}(\mathrm{t})$	Power generated by PSP during generating mode at t_{th} time
$P_{gen}(\mathrm{t,s})$	Power generated by PSP during generating mode at t_{th} time of s_{th} scenario
$\bar{P}_{gen}(\mathrm{t})$	Planned value of PSP generation at t_{th} time
$\hat{P}_{gen}(\mathrm{t})$	Optimal min-max value of PSP generation at t_{th} time
$P_{gen}^{\min}$	Minimum generating limit of PSP
$P_{gen}^{\max}$	Maximum generating limit of PSP
PJM	Pennsylvania-New-Jersey-Maryland market

P_{loss}	Power loss due to market Imbalance
$P_{loss}(t)$	Power loss due to market Imbalance at t_{th} time
P_m	Mechanical Power
Pp(t)	Power consumed by PSP during pumping mode at t_{th} time
$P_p^{\min}$	Minimum pumping limit of PSP
$P_p^{\max}$	Maximum pumping limit of PSP
P_{pump}	Power consumed by PSP during pumping mode
Ppump(t)	Power consumed by PSP during pumping mode at t_{th} time
Ppump(t,s)	Power consumed by PSP during pumping mode at t_{th} time of s_{th} scenario
PSO	Particle Swarm Optimization
PSP	Pumped Storage Plant
P_{wind}^{-}	Wind Power at uncertainty risk is at maximum value
P_{wind}^{+}	Wind Power at uncertainty risk is at minimum value
$Pw_{gen}(t,s)$	Total power generate by WPP at t_{th} time in *MWh* at t_{th} time of s_{th} scenario
$Pw_{pump}(t,s)$	Power supplied by WPP for pumping operation at t_{th} time of s_{th} scenario
$Pw_{mkt}(t)$	Power supplied by WPP to market at t_{th} time
$Pw_{mkt}(t,s)$	Power supplied by WPP to market at t_{th} time of s_{th} scenario
$Pw_{pump}(t)$	Power supplied my WPP for pumping at t_{th} time
$\tilde{P}_{wind}^{s}(\mathrm{t})$	Uncertain power supplied by WPP at t_{th} time of s_{th} scenario
$\overline{P}_{wind}(\mathrm{t})$	Fixed planned value of wind power at t_{th} time
$\Delta\tilde{P}_{wind}(\mathrm{t})$	Variable or uncertain value of wind power at t_{th} time
q_p	Rate of flow (discharge) by PSP in pumping mode
q_t	Rate of flow (discharge) by PSP in generating mode
R	Risk
r	Total number of testing
RES	Renewable Energy Source
$R_{gen}(t)$	Revenue during generating mode of PSP at t_{th} time in *Rs*

$R_{gen}(t,s)$	Revenue during generating mode of PSP at t_{th} time of s_{th} scenario in *Rs*
$R_{loss}(t)$	Revenue loss at t_{th} time in *Rs*
$R_{loss}(t,s)$	Revenue loss at t_{th} time of s_{th} scenario in *Rs*
$R_{loss}(t,s)$	Revenue from total market imbalance at t_{th} time of s_{th} scenario in *Rs*
$R_{psp}(t)$	Revenue of PSP at t_{th} time in *Rs*
$R_{psp}(t,s)$	Revenue of PSP at t_{th} time of s_{th} in *Rs* scenario
$R_{pump}(t)$	Revenue during pumping mode of PSP at t_{th} time in *Rs*
$R_{pump}(t,s)$	Revenue during pumping mode of PSP at t_{th} time of s_{th} scenario in *Rs*
Rs	Indian Rupees
$R_{wind}(t)$	Revenue of WPP at t_{th} time in *Rs*
$R_{wind}(t,s)$	Revenue of WPP at t_{th} time of s_{th} scenario in *Rs*
$s(t)$	Switching state of PSP unit during generating mode at t_{th} time
$s(t,s)$	Switching state of PSP unit during generating mode at t_{th} time of s_{th} scenario
SCUC	Security-Constrained Unit Commitment
S_i	Range for i_{th} scenario
SMES	Superconducting Magnetic Energy Storage
$sp(t)$, $sp_a(t)$, $sp_b(t)$	Switching state of PSP unit during pumping mode at t_{th} time
$sp(t,s)$	Switching state of PSP unit during pumping mode at t_{th} time of s_{th} scenario
Δt	Time deviation or Time interval
T&D	Transmission and Distribution
TR	Total Revenue in *Rs*
UK	United Kingdom
USA	United State of America
V	Wind Velocity
VaR	Value at Risk
V_{ci}	Cut-in wind speed for wind turbine
V_{co}	Cut-out wind speed for wind turbine
V_i	Velocity of wind at i_{th} scenario

V_{max}	Maximum velocity of wind
V_{min}	Minimum velocity of wind
V_r	Rated wind speed for wind turbine
VRB	Vanadium Redox Battery
V_t	Upper reservoir Volume at t_{th} time
WEG	Wing Energy Generation
WGENCO	Wind Generation Company
WPP	Wind Power Plant
WWEA	World Wide Energy Association
η_e	Electrical Generator Efficiency
η_h	Efficiency of PSP during generating mode
η_m	Mechanical Efficiency
η_p	Efficiency of PSP during pumping mode
ρ	Wind Density
Ω	Penalty Factor

CHAPTER–1

INTRODUCTION

1.1 GENERAL

The world presently is facing major environmental challenge in meeting growing energy needs due to the effect of global warning and erratic weather patterns. Oil insecurity, rising fossil fuel prices and concerns about climate change cast a shadow over the future use of coal, oil and other conventional energy sources (Weisser and Garcia 2005; Sharma et al. 2012; Tiwari and Mishra 2011). The increase in energy price encourages the search for cost competitive alternate sources of energy to achieve environmental sustainability (Asif and Muneer 2007; Hiremath, Shikha, and Ravindranath 2007; CPCU 2005). Energy from renewable sources like wind, solar and water is inexhaustible, reliable and clean. Various governments worldwide including India are setting up the targets for renewable energy generation capacity additions. A target of 15% of renewable energy contribution in overall energy needs have been projected by the year 2020 though major policy measures are required to meet such target (Kaldellis 2004; Kaldellis et al. 2001).

Presently about 19% of world's total energy is supplied by renewable energy sources (RESs) as shown in Fig. 1.1 (REN21, 2014). About 9% out of total renewable energy supply is from traditional biomass, 3.8% is from hydropower and 6.2% from other RESs such as solar, wind, modern bio-energy and geothermal. Sustainable and environment friendly development may be the best achieved probably through development of RESs. Renewable energy contribution in power generation is growing rapidly by an annual average of 15%. Total renewable power capacity worldwide exceeded 1,560 GW in 2013, which is more than 8% compared to the year 2012. Hydropower capacity rose by 4% in the year 2013 to a total installed capacity of about 1000 GW. Wind energy capacity rose by 12.4% in the year 2013 to a total installed capacity of 318 GW, while other renewables grew 22.8% to take total capacity to 242 GW in 2013 as shown in Fig. 1.2. By the year 2014, renewable energy may comprise more than 26.4% of global electricity generating capacity and supply an estimated 22.1% of global electricity, where 16.4% of electricity can be supplied by hydropower source. Industrial, commercial, and residential consumers are increasingly becoming producers of renewable energy in many countries (REN21, 2014).

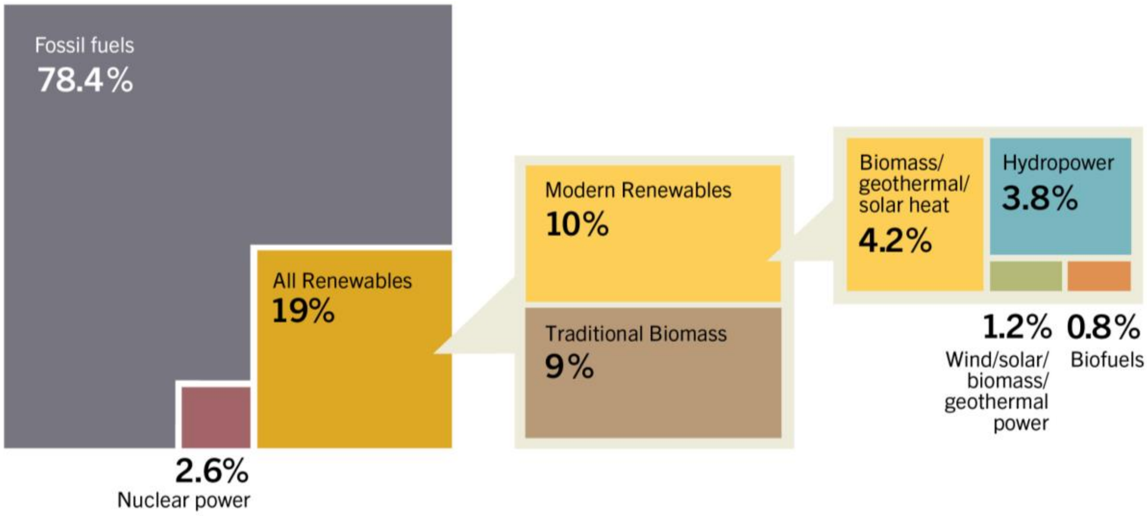


Fig. 1.1: Global renewable energy consumption (%) at the end of 2013 (REN21, 2014)

1.2 WIND POWER

Wind is the renewable energy source driven by the sun. The wind is set in motion by the differences in temperature and air pressure due to solar radiation on the earth surface (Patel 1942; Kaldellis 2004; Kabouris and Perrakis 2000; "Wind Power" 2014). The energy of wind has been utilized for long time. Some of the oldest applications of wind energy include cereal grinding, water pumping and other applications related to agriculture sector. Today electricity from wind power plants (WPP) can be generated at competitive costs and contribution from wind energy is an appreciable part of the power capacity in many countries (Earnest and Wizelius 2011). In spite of uncertain characteristic of the wind and the fluctuations of market demand, wind energy has penetrated many parts of world including Europe, China, India and USA but with strict limits mainly due to technical barriers to protect the instability problems in the autonomous electrical grids ("Wind Power" 2014; Earnest and Wizelius 2011).

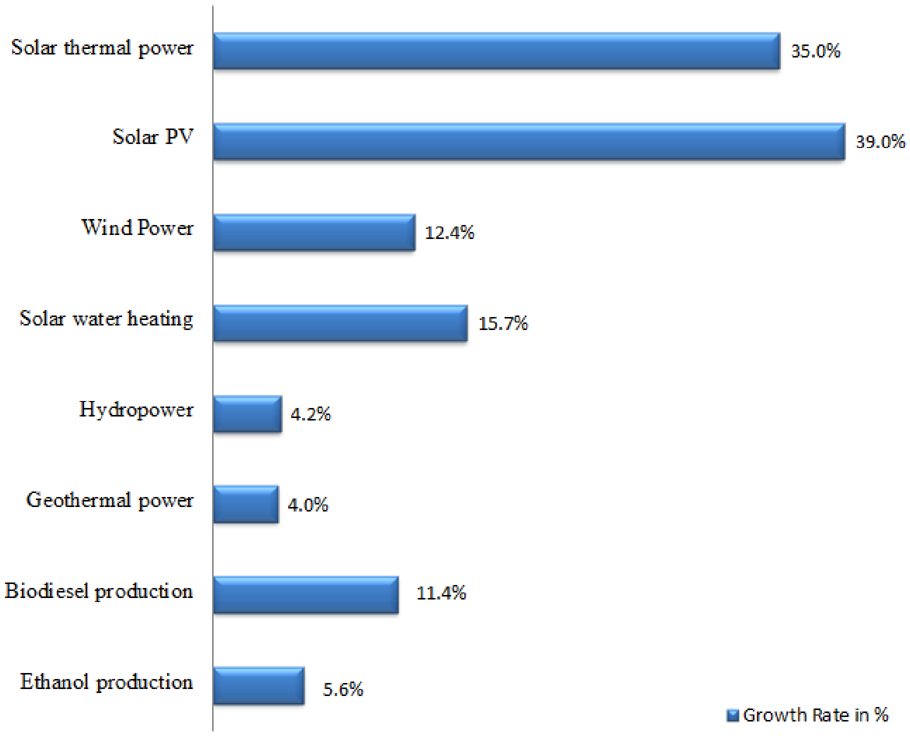


Fig. 1.2: Average annual growth rates of renewable energy capacity and biofuels production (REN21, 2014)

1.2.1 Wind Power : Global Scenario

Wind energy has the fastest growth rate of any form of electricity generation presently and is attributing mainly to concerns of national policy makers over climate change, energy diversity and security of supply. According to global wind energy council (GWEC) and world wind energy association (WWEA), the growth rate of wind energy will increase rapidly in future as shown in Fig. 1.3 (WWEA 2014; REN21 2014; GWEC 2013). The wind power capacity predicted to be installed by the year 2018 is 596 GW and the projected annual growth rates during this period will be average 13%. Five leading countries viz China, Germany, USA, Spain and India, represent together a total share of 72% of the global wind capacity (GWEC 2013; Earnest and Wizelius 2011; WWEA 2014; Vieira and Ramos 2009; Joselin et al. 2007; Shafiullah et al. 2013; Islam, Mekhilef, and Saidur 2013; Hedegaard and Meibom 2012; Hessami and Bowly 2011; Ding, Hu, and Song 2012). With the development of wind turbines from small to large capacity, wind power has become more competitive (GWEC 2013). Several off shore wind farms are already on line in Europe. There are plans to develop more off-shore wind power plants (WPPs) (Earnest and Wizelius 2011; Ackermann 2005).

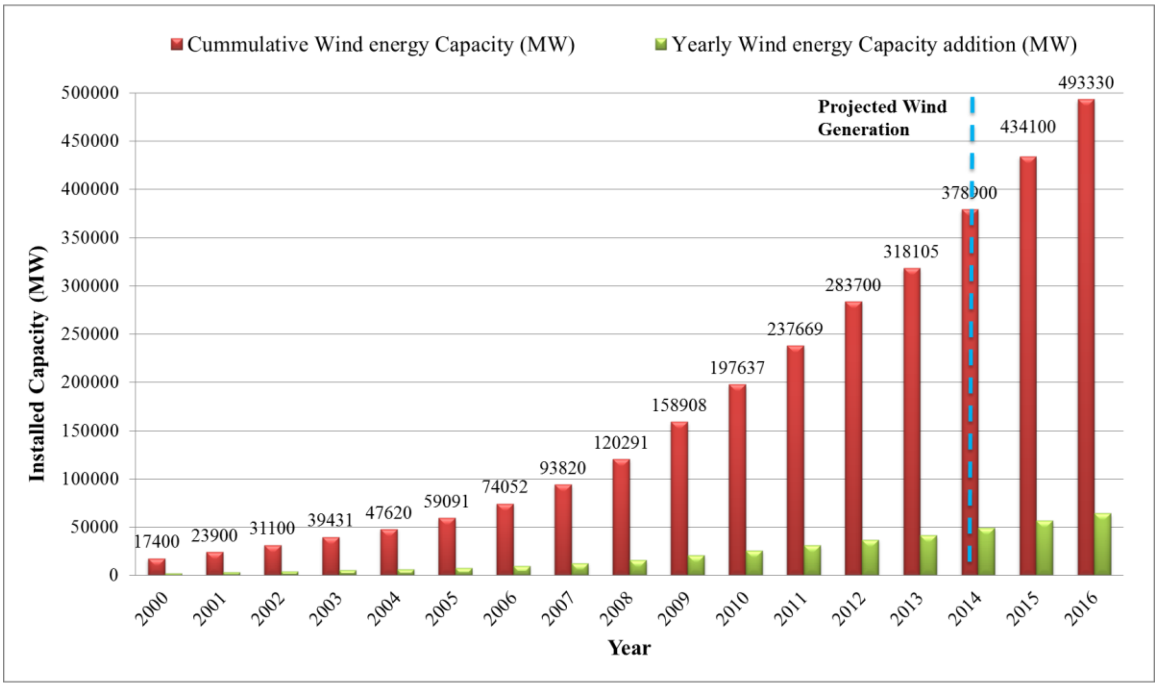


Fig. 1.3: Global wind energy installed and projected capacity (GW) (GWEC 2013, WWEA 2014)

1.2.2 Wind Power : Indian Scenario

After the 1990, there is a significant increase in the development of wind power in India, a relative beginner to the wind power generation compared with United States and Denmark and has the fifth largest installed wind power capacity in the world. During 2009-10, India added the highest wind capacity compared to the other top four countries (WWEA 2012). With over 20 GW installed capacity, wind energy is the fastest growing renewable energy in India and currently accounts for almost 62% of the total installed capacity excluding hydropower. The 12th five year plan proposals (year 2012-2017) visualize around 15 GW of grid connected renewable power capacity addition from wind energy alone. Under the New Policy Scenario, total power capacity in India for all energy sources would reach 779 GW in 2035 requiring capacity addition of over 25 GW per year. More than 95 percent of the India’s wind energy generation is concentrated in five states namely – Tamil Nadu (7251 MW), Maharashtra (3472 MW), Gujarat (3384 MW), Karnataka (2312 MW) and Rajasthan (2734 MW). State wise wind installed capacity as on 31-01-2014 is shown in Fig. 1.4 (GWEC 2014).

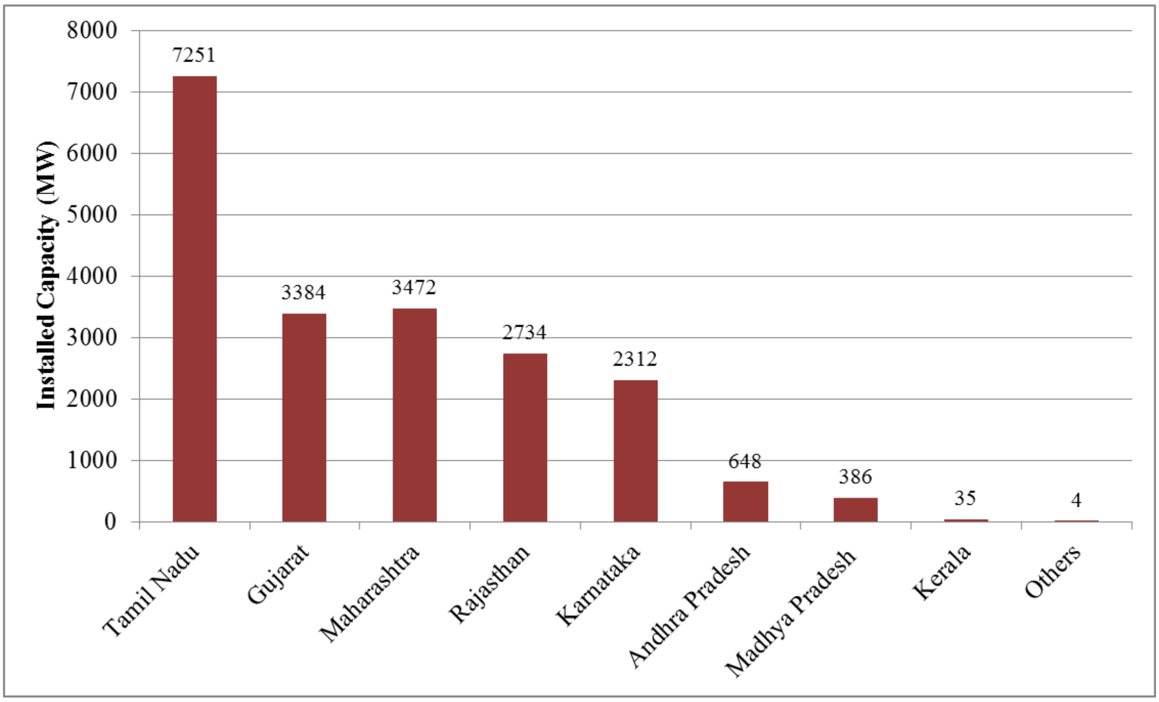


Fig. 1.4: State wise wind installed capacity (MW) as on 31-01-2014

1.2.3 Wind Energy Applications

Large numbers of wind energy projects, both onshore and offshore are being installed around the globe. Onshore wind energy project installations are mostly in upland terrain to exploit the higher wind speeds. Wind projects siting onshore can be difficult as high wind-speed sites are often environmentally sensitive and having high visual amenity value. The advantage of offshore wind projects include intrusion and acoustic noise impact and also lower wind turbulence with higher average wind speed. The obvious disadvantages are higher construction costs and operating wind turbines requires longer transmission lines to connect with the grid. Smaller wind projects can also be used for rural electrification with applications including village power systems and stand-alone wind systems for hospital, residences and community centers.

1.2.4 Wind Power – Development Challenges and Opportunities

In spite of several advantages, wind power today faces lot of challenges and barriers at the implementation level, especially in developing nations like India. Barriers in harnessing wind power can be classified as follows (Earnest and Wizelius 2011; Hedegaard and Meibom 2012):

i. Technical Barriers

The technical barriers faced by wind power are non-availability of grid and capacity, lack of access to transmission lines, network integration issues e.g. voltage level, power imbalances, reliable short circuit power control, flicker control and harmonics control etc. Operational issues are short-term balancing, long-term balancing, stability in network grid, frequency control, unit commitment and economic dispatch etc. Lack of data to forecast wind profiles, reliable wind resource assessments, proper siting and sizing of WPPs are also some challenges for wind power development.

ii. Financial barriers

Financial barriers are the high initial capital costs, uncertainty regarding the financial performance e.g., losses due to lower generation and the cost of transmission lines from a wind farm to the grid. Such barriers result in unattractive investment by the private investors, particularly in developing countries due to lacking of financial institutions for the financing of such long-term projects with uncertainty.

iii. Market Barriers

Lack of institutions to facilitate contracts (power purchase agreements) between wind energy developers and operators of the system, lack of policies favorable to wind energy development and lack of long-term value for real-time or day-ahead markets where a wind energy project can attract bulk investors are the few notable market based barriers to wind power development.

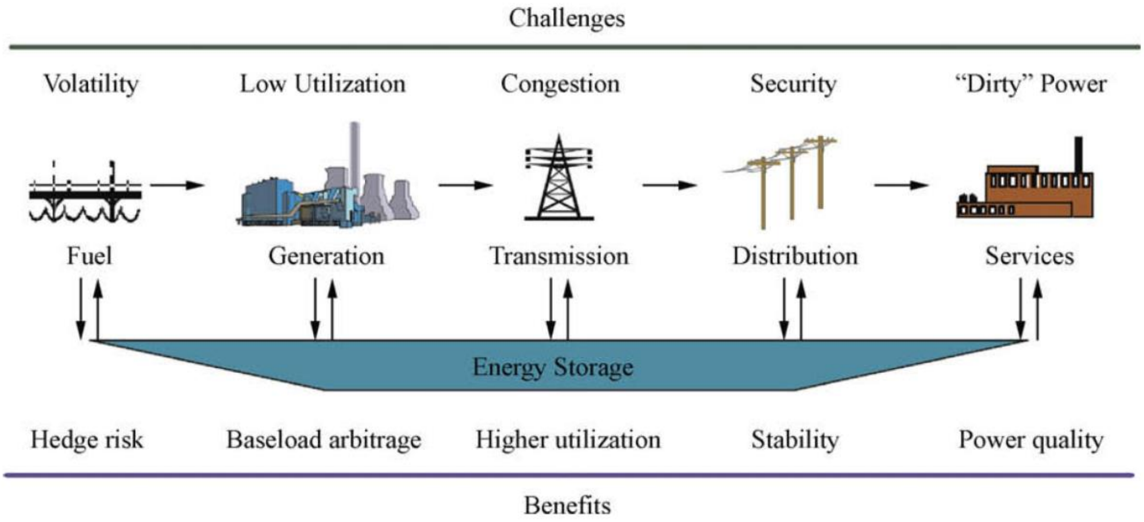
Wind power generation has an edge over the other renewable energy due to its technological maturity, good infrastructure, competitive cost and environmental benign nature (Shafiullah et al. 2013). Germany, Denmark, Spain, Great Britain, India, China and United States, are installing wind power plants on a large scale, in an ever increasing pace. Advanced wind technology is expected to be more efficient, more robust and less costly than current technology (Islam, Mekhilef and Saidur 2013). Further research is required in many other areas, e.g. wind turbine technology and network integration of medium/high penetration of wind energy. The maximum penetration of wind power in electricity networks is limited by its intermittent nature of energy and can lead to problems related to system operation and the planning of power systems. It is important to note that for the fi-rst time, dynamic markets can be found on all continents. The largest markets for new and advanced wind turbines technology and promising market with encouraging policies are Sweden, Australia, Denmark, Romania, Canada, Brazil and Latin American.

1.3 ENERGY STORAGE SYSTEMS (ESSs)

Wind is classified as ‘‘negative load’’ (or ‘‘non-dispatchable’’) by electricity regulators and not relied upon to meet the demand at critical times (Hessami and Bowly 2011; Ding, Hu, and Song 2012). Like any other sources of energy wind has its own strengths and weaknesses. The primary limitation is inherent variability and regarded as unstable source of power. Thus proper tools are required to predict the wind power generation uncertainties, involved in the integration of a wind source to the system. Until recently, characteristics of wind speed and direction were predicted only by weather analysis (Islam, Mekhilef, and Saidur 2013; Hedegaard and Meibom 2012; Ding, Hu, and Song 2012; "Electricity storage" 2013; "Electricity storage association" 2013; Muyeen et al. 2009). Several literary articles are available where different forecasting techniques have been used to map wind data for several days in advance. However, research is still going on for scheduling of wind plants to meet the demand of the grid.

1.3.1 Applications of Energy Storage Technologies

Wind power output can be stored using energy storage systems (ESSs) at times of low demand and the same power from ESS can be used during high demand period. In recent years, large efforts are being made around the world to develop wind energy resources in response to energy shortage and environmental problems (Zhang et al. 2013). Some of the key applications of ESSs in wind integration are to provide better voltage regulation, less frequency deviation at the transmission & distribution level and maintain power quality, by providing peak shaving, load following, spinning reserve and demand-side management (Beaudin et al. 2010; Ibrahim, Ilinca, and Perron 2008; McDowall 2006; Hall and Bain 2008; Liu and Jiang 2007; Ter-Garzarian 2011; Ferreira et al. 2013; "Energy Storage" 2013; "Energy Storage – Packing some power" 2013). The traditional electricity value chain consist of five links i.e. (a) fuel/energy source, (b) generation, (c) transmission, (d) distribution and (e) customer-side energy service connected to ESSs as



shown in Fig. 1.5.

Fig. 1.5: Application, benefits and challenges of energy storage system along the electricity value chain (Makansi and Abboud, 2002)

The energy storage technologies provide an economic incentive to wind power generators by receiving higher revenues from the power supply to the electricity market, when the spot price is high (Dinglin et al. 2012). Wind farm energy storage can be classified as a partially dispatchable source due to its ability to respond the situations of high demand. Large scale energy storage at present is not widely used because of the centralized nature of traditional electricity generation. Reports by Electric Power Research Institute (EPRI) and Sandia Laboratory, USA described the possible applications of energy storage in the generation, transmission and distribution levels, explored the benefits of technology, and provided cost estimates for each technology, application of load change, support frequency and power quality (EPRI, 2003a, 3003b, 2004, 2010a 2010b; Schoenung, 2001, 2011; Schoenung and Hassenzahl, 2003, 2007).

1.3.2 Energy Storage Technologies Classification

Present energy storage capacity worldwide is equivalent to about 128 GW only which is 1.6% out of total installed capacity of 7,740 GW (REN21 2014; Tsung-Ying 2008; “Electricity Storage” 2013). Many energy storage options (small, medium and large capacity) have been reported in the literature such as pumped storage plant (PSP), compressed air energy storage (CAES); batteries including lead-acid (Pb-acid), sodium-sulfur (NaS), nickel-cadmium (Ni-Cd), lithium Ion (Li-ion) batteries, vanadium redox flow battery (VRB), zinc and bromine flow battery (ZnBr), superconducting magnetic energy storage (SMES), electrochemical capacitors (EC) and flywheels. Wind power operators receive higher income for supplying power to the grid during periods of peak electricity demand when the spot price is high (Hedegaard and Meibom 2012; McDowall 2006). A large-scale research in the use of energy storage to complement wind energy has been reported in the literature (Hedegaard and Meibom 2012; Ding, Hu, and Song 2012; Dinglin et al. 2012; Tuohy and O’Malley 2011; Beaudin et al. 2010; Ibrahim, Ilinca, and Perron 2008; McDowall 2006; Hall and Bain 2008; Ter-Garzarian 2011).

1.3.3 Comparison of Various Energy Storage Technologies

The ESS technologies have been compared based on various factors like power capacity, energy capacity, efficiency, lifetime etc. and is presented in Table 1.1 (Díaz-González et al. 2012; Ferreira et al. 2013; Georgilakis 2008; Kaldellis and Zafirakis 2007; Schoenung and Hassenzahl 2007; Schoenung and Hassenzahl 2003; Schoenung 2001, 2011; Swierczynski et al. 2010; Abbey and Joos 2006). To smoothen the use of wind power, past studies have focused on the coordination of ESSs with WPPs. The pumped storage plant (PSP) has been considered as the most mature technology having the largest capacity at acceptable cost (Ding et al. 2012).

The major challenges as well as benefits of ESSs are shown in Fig. 1.6; where classification of ESS is shown as a function of investment cost per unit of power verses unit of energy (Electricity Storage Association 2013). The technologies used for energy storage have different characteristics and are at different stages of maturity. Technologies such as compressed energy storage and lead-acid batteries are also proven technology but have the limitation for capacity. Today, there are large scale efforts to improve the capabilities and efficiency of storage technologies as well as reducing their capital cost. The aim of these developments is to make storage technologies economically suitable for greater penetration of intermittent renewables energy into the electricity system (Ibrahim, Ilinca, and Perron 2008; Díaz-González et al. 2012)

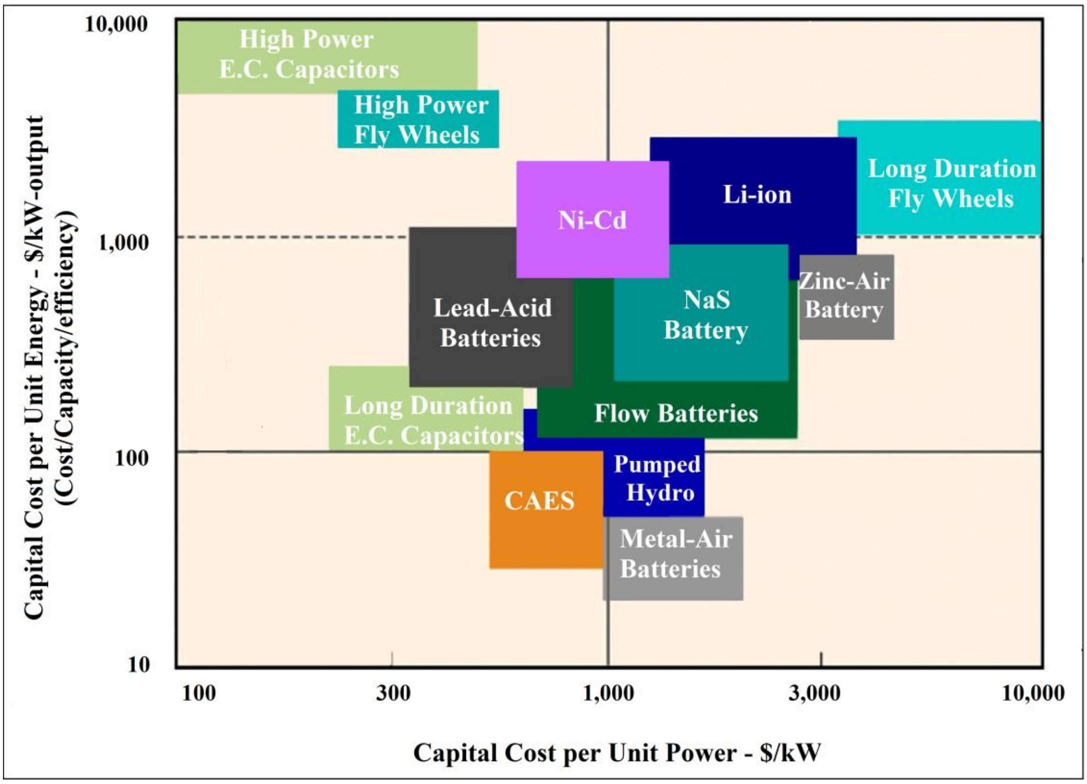


Fig. 1.6: Classification of ESSs as a function of investment costs per unit of power or unit of energy (Electricity Storage Association 2013)

Table 1.1: Comparison of various ESS technologies

Technology Type	Storage Capacity (MWh)	Power Capacity (MW)	Energy Density (kWh/m^3)	Life cycle (years)	Access time	Self-discharging	Efficiency (%)	Power/ Energy	Environment Impact	Application	Installation Examples	Suitability with wind (Yes/No)
Flywheel	2.5	25	1000	20 Year	ms (millisecond)	1-10%	90-95	25 MW for 5 min or 5 MW for 30 min	Small	Power quality improvement and Transportation defense	-Usually utilized for UPS -Propulsion applications like engines and road vehicles	Yes
Capacitors	Small	Large	5	10^6 Cycles	ms	10% day	90-95	Rated power for sec. up to several min	Medium	Power quality, emergency bridging power, Consumer electronics	---	Yes
SMES	0.5-5	10	2.8	20 Year	ms	Cooling power	90-95	High power for several sec	Small	Power quality and T&D applications	-Several uses in power quality control -In Wisconsin, a string of distributed SMES units was deployed to enhance stability of a transmission loop	Yes
NaS Battery	Up to 1200	Up to 200	400	4500 cycles up to 15 year	ms	No	80-90	Rated power for hours, very high power for minutes	Medium	Variability reduction, Uninterruptable power supply (UPS), T&D applications, Power quality improvement	-Rokkansho, Japan 34 MW/245 MWh -Hittachi Plant 8MW/58 MWh	Yes
Pumped Storage	500-8000	30-4000	-	Up to 50 Year	1-3 minute	No	70-85	Rated power for long time	High	Spinning/standing reserve, energy arbitrage	There is over 90 GW in more than 240 Pumped storage facilities in the world	Yes
CAES	500-2500	50-300	-	Up to 40 Year	10 minute	-	64-75	Rated power for long time	Medium	Spinning/Standing reserve, energy arbitrage, Frequency regulation	-Huntorf plant, Germany, 290 MW580 MWh -Mclntosh plant, USA, 100 MW, 2600MWh	Yes
Hydrogen	1000	100	-		-	-	30-50	Rated power for long time	Medium	Variability reduction, Spinning/Standing reserve	----	Yes

1.4 PUMP STORAGE SYSTEM (PSP)

Electricity storage has the potential benefit of penetration of wind technology in the market to enhance the value of wind generation. All storage technologies discussed above are viable and proven energy storage methods; though each technology is limited in some way specifically with respect to wind energy. The seasonality of wind requires a storage system not for few hours in the day but also over months in the year. Wind energy needs an energy storage system having the ability to store thousands of Megawatts over daily and seasonal horizon, the ability to ramp up and down quickly according to real time changes in wind energy output with reasonable conversion efficiency. Today, the only storage technology that is consistent with these requirements is the PSP (Ding et al. 2012). Using wind forecasting, storage based hydropower plants can adjust their storage and discharges so that these provide energy to the system almost instantaneously, operating much like a peak load plant (Abbey and Joos 2006; Sundararagavan and Baker 2012; Kazempour et al. 2009; Benitez et al. 2008; Yadav et al. 2011; Yang 2011).

PSP is a large scale energy storage system. Its working principle is based on the management of water potential energy by pumping water from lower reservoir to upper reservoir during periods of low power demand and during peak demand water flows from the upper reservoir to the lower reservoir to generate electricity using hydro turbines. The stored energy is proportional to the volume of water in the upper reservoir and the difference in elevation of water in reservoirs (Díaz-González et al. 2012; Sundararagavan and Baker 2012; Kazempour et al. 2009; Benitez et al. 2008; Kapsali and Kaldellis 2010; Pickard, Shen, and Hansing 2009; Dursun and Alboyaci 2010; "Electricity Storage 2013; "The principles of pumped storage" 2013). Pumped storage plant has been set up at commercial level in many countries, having suitable topography (Díaz-González et al. 2012). In general, the lifetime of PSP facility is about 30-50 years, with an efficiency in the order of 70% to 80%, even some claiming upto 87% (Jacob 2013) and the capital costs ranging from 500-1500 US $ / kW with energy cost as 10-20 US cent/kWh (Kaldellis and Zafirakis 2007).

Pumped storage is the largest available capacity form of grid energy storage which accounts for more than 99% of bulk storage capacity worldwide, representing around 127 GW. There are approximately 270 PSP around the world either in operation or under construction. Out of the total facilities, 36 are adjustable speed drives type, 17 of which are currently in operation (totaling 3,569 MW) and 19 of which are under construction (total 4,558 MW). It is anticipated that this capacity may exceed 203 GW in 2014, representing an annual growth of 10%. The current geographical distribution of PSP worldwide is shown by Fig. 1.7.

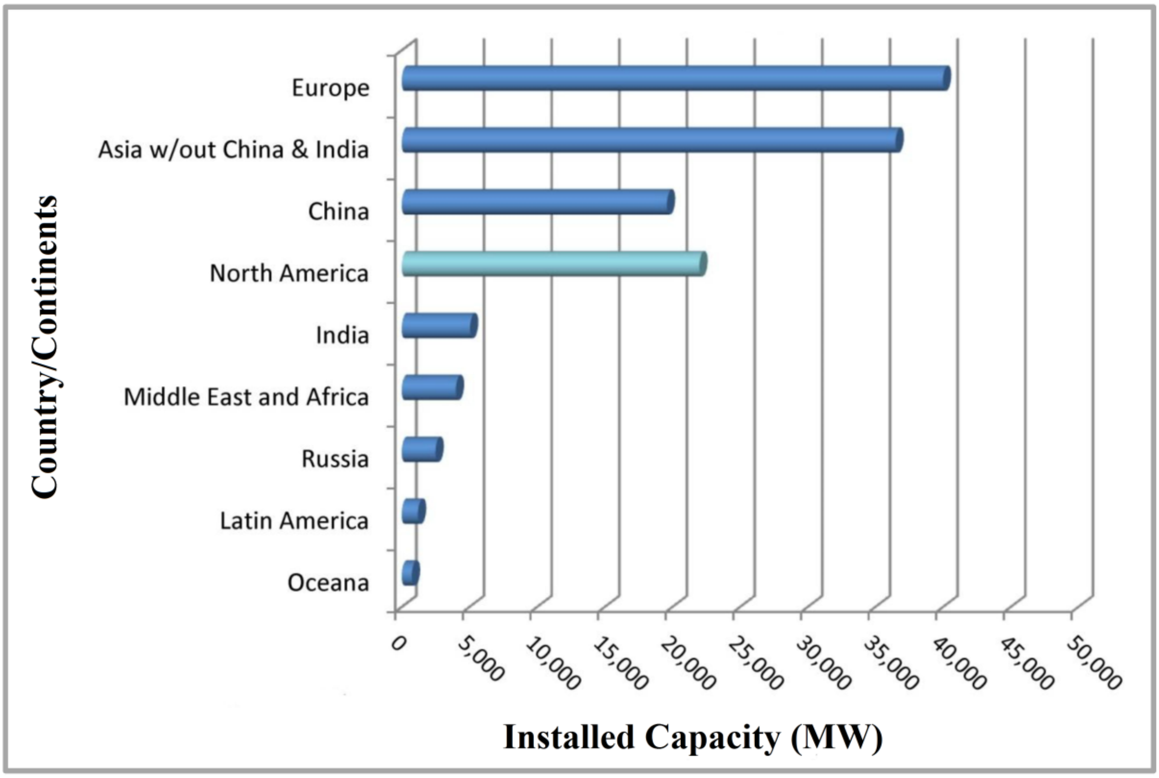


Fig. 1.7: Pumped storage hydro power plant arrangement (NHA 2013)

The capital costs, suitable geography and the impact on environment are critical factors for the feasibility of PSP. New techniques of utilizing underground caverns or subsurface reservoirs are opening up the possibilities of using PSP in areas without mountains.

Recent examples of PSP in plain area include the proposed Summit project in Norton (USA) and the Mount Hope project in New Jersey (USA), where old iron mine is being used as the lower reservoir (Schoenung 2001). Though cost estimates for these projects are higher than surface reservoir based projects, but their use might expand the number of pumped storage sites. A 30 MW, Yanbaru PSP project in Okinawa was the first demonstration project of seawater pumped storage (MWH, 2009). A 300 MW seawater based project in Lanai, Hawaii and several seawater-based projects in Ireland have been recently proposed (“Pumped Storage Hydroelectricity” 2013; Miller 2013). Planning of pumped storage needs a detailed study of the power system regarding availability of surplus energy to ensure projected performance bench-mark and financial efficiency.

1.5 WIND-PSP SYSTEM

Among the different possibilities of controllable power to operate in coordination with wind power, PSP is the most feasible solution due to its flexibility as the output power can be changed almost 100% in few minutes. Its ability to quickly change the output power is the key feature to follow the short term variations of wind power (Ibrahim, Ilinca, and Perron 2008). A PSP, having the ability to store water, when combined with availability of wind power is regarded as a wind-pumped storage plant (Wind-PSP) (Caralis, Rados, and Zervos 2010; Montero and Perez 2009; MWH 2009; Perez and Fernando 2009).

The combined use of Wind-PSP is considered as means to exploit the abundant wind energy potential, increases the wind installed capacity and substitutes conventional peak supply (Nguyen Ngoc et al. 2009). Large scale integration of wind power in power system requires large ESS. In the recent years the combined use of wind-PSP is getting attention from the scientific community. Shaping of wind variability may be observed by integrating wind with pumped storage as shown in Fig.1.8 (Miller 2013).

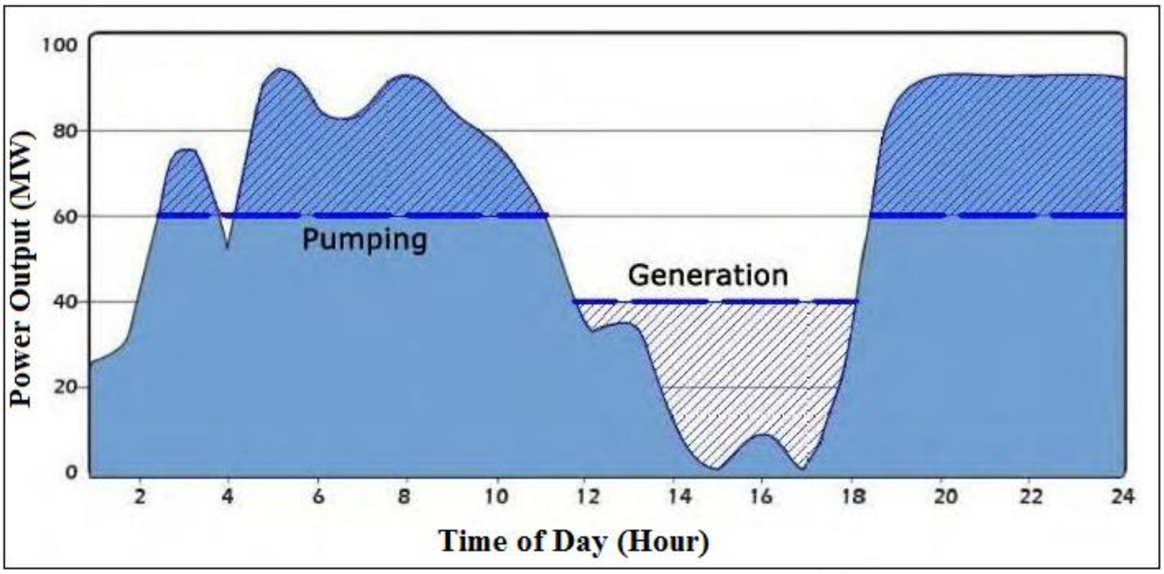


Fig. 1.8: Integrating wind with pumped storage for shaping wind variability

1.5.1. Typical Arrangement of Wind-PSP System

In a typical system of Wind-PSP, kinetic energy available through wind is used to power the PSP to pump water from a lower reservoir to the reservoir at higher elevation. By doing this, the PSP effectively stores wind energy in the upper reservoir and uses this stored energy to generate electricity during peak demand by flowing water from upper reservoir to lower reservoir. At times of low electricity demand, excess electrical capacity is used to pump water into upper reservoir. When there is higher demand, water is conveyed from upper reservoir to the lower reservoir through a turbine, generating hydropower. In this process, 70% to 85% of the electricity consumed in pumping can be recovered.

A typical arrangement of wind-PSP system is shown in Fig. 1.9 (Anagnostopoulos and Papantonis 2007; Miller 2013; "Pumped Storage Hydroelectricity" 2013). Integration of a pumped storage unit in electrical networks has great importance in view of reduced cost of combined wind-PSP system operation, as the generating power unit of this type can operate not only with stored water using wind energy, but also with any other energy generation system such as hydro, solar thermal etc.

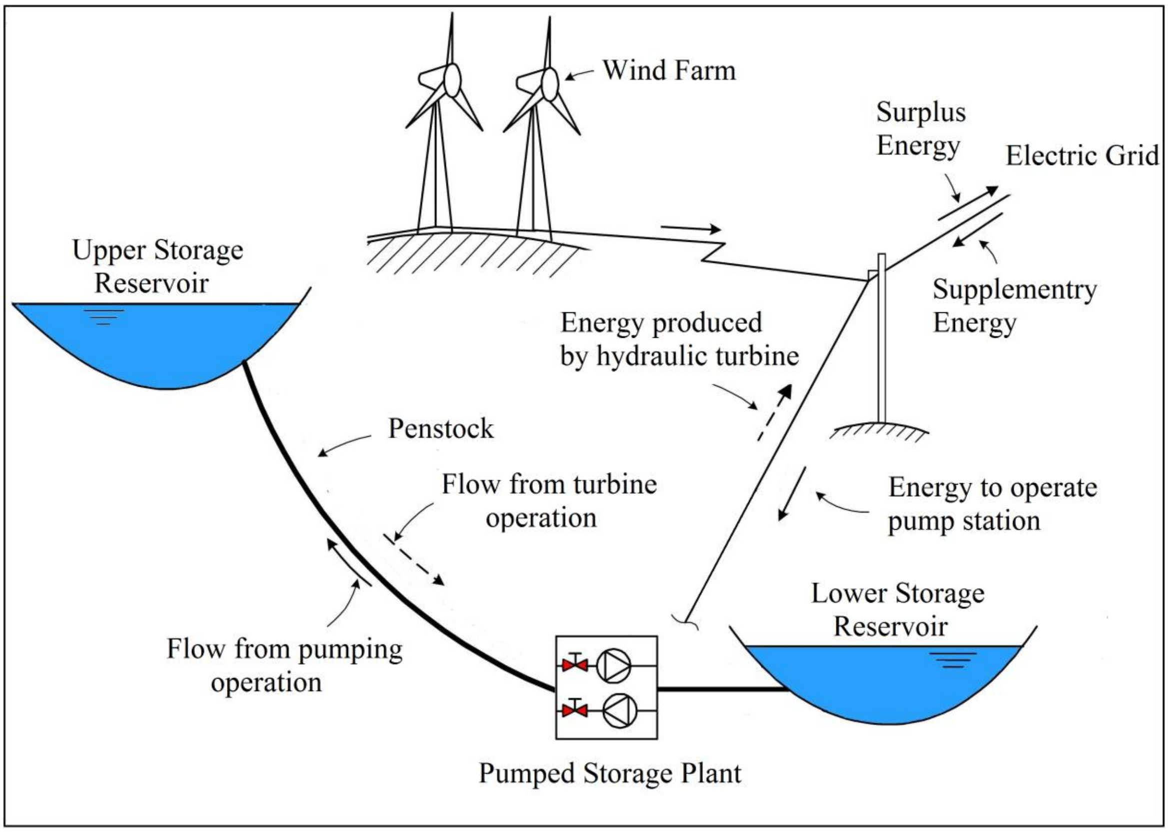


Fig. 1.9: A typical arrangement of wind-PSP system (Anagnostopoulos and Papantonis 2007)

Due to advancement in wind energy technology and energy storage, wind power is expected to penetrate more into the electrical grid and therefore wind energy is no more considered as a marginal source. The production of wind energy increases fluctuations in the electricity network system therefore more restrictions are introduced to wind energy producers, for example: limited variation of injected power and higher quality service (current and voltage profile, ancillary services), etc. (Nguyen Ngoc et al. 2009). Recent wind-PSP application trends in Europe show an increase in wind energy upto 8% of energy (53 GWh) In selected regions, the penetration is more than 20% with adjustable/variable speed and there is focus on new and re-optimization of existing plants. European approach towards pumped storage is spreading globally now. In Denmark, there is 30% wind penetration in the generation mix with no negative load balancing. Excess wind energy is exported and stored in Norwegian hydropower reservoirs (“Renewable Energy World” 1999).

The Alta Mesa pumped storage facility near Palm Springs, CA, USA uses wind generated electricity to accomplish the pumping to the upper reservoir. The Pumped Storage project is a 70 MW energy storage facility. This facility is able to store 420 MWh and produces electricity for 6 hours continuously. Additionally, this project produces 130,000 MWh per year of high-value on-peak power, and uses 175,000 MWh per year of low-value off-peak power (“Alta Mesa Pumped Storage” 1996).

During the recent years, a number of studies have been performed on the development of wind-PSP systems mainly in USA and Europe. Since its introduction, Wind-PSP technology has advanced significantly over the years with improved efficiencies through modern reversible pump turbines, pump turbines of adjustable speed, new control equipment such as static converters / variable frequency generator insulation systems, improved methods and construction of an underground tunnel design capabilities. In general, the efficiency of pumping cycle / generator has increased pump-turbine generator efficiency by as much as 5% in the past 25 years, resulting in power conversion efficiencies greater or 80% duty cycle (MWH 2009).

1.6 WIND-PSP CONCEPT

For the efficient operation of wind-PSP system and maximization of the profit, some operation management tools are required. Wind as well as PSP systems have their own merits and demerits. During the integration of both the systems, one can compensate the demerits and work as complimentary to each other to provide the efficient operation (Vieira and Ramos 2008, 2009; Angarita, Usaola, and Martínez-Crespo 2009; Caralis, Rados, and Zervos 2010; Nguyen Ngoc et al. 2009; Manolakos et al. 2004; Dursun and Alboyaci 2010; Suul 2008).

Under the deregulated market, power producers place their energy bid in the market. Power producer has to pay the penalty for any market imbalances, which may occur due to difference between the contracted and actually produced wind energy. For avoiding penalties, the impact of wind uncertainties are to be reduced. For this, power producers need ESSs, which can maintain the reliability and balance across the power system. Pumped storage technology is always seen to be the best option as an ESS for WPPs and provides significant flexibility in switching operation. The different modes of operation of wind-PSP are as follows (Sundararagavan and Baker 2012; Wood and Wollenberg 2006; Dhillon et al. 2012, 2013):

i. **PSP Generating Mode:** In this mode, PSPs supply power to the grid connected day-ahead market and try to increase their revenue. Both wind and PSP pumps remain at their idle condition.

ii. **PSP Pumping Mode:** In this mode, PSPs operate in pumping mode to consume the wind generated power and store it in upper reservoir in the form of water.

iii. **Grid Pumping Mode:** In this mode PSP utilizes the grid power via pumping action and store it in the upper reservoir in the form of water. Mostly this operation is done whenever the market price of electricity is low.

iv. **Wind Generating Mode:** In this case, WPP supply the power directly to the grid and PSP remains at its ideal condition.

v. **Wind-PSP Mode:** In this mode, there may be two instances (a) both wind and PSP system generate to meet the demand, (b) Wind system generates to meet the demand as well as supply the power for pumping operation.

1.7 CHALLENGES AND OPPORTUNITIES FOR WIND-PSP DEVELOPMENT UNDER DEREGULATED MARKET

There are several benefits of combined wind-PSP, however there are many challenges also. The challenges are concerning to the operational aspects of wind-PSP as well as its penetration with different types of market ensuring that the generation of electric power meets the real time demand through grid reliability. The primary challenge involved is to generate power as per the real time demand as electricity does not have a shelf life. Electricity demand changes continuously, especially between periods of peak time and low demand. Further development of wind-PSP, especially in areas with marginal increase in wind capacity and PSP, can significantly improve network reliability reducing fossil fuel based generation. While the benefits of wind capacity expansion-PSP are clear, current market structures and regulatory frameworks are still ineffective in achieving such goal. Thus changes in policies are needed to support the development of energy storage at large scale (DeCesaro and Porter 2009; "Schubert et al. 2002; "Renewable Integration" 2010).

1.7.1. Major Challenges to Wind-PSP Systems

1.7.1.1. Wind Power Challenges

For optimal management system, information about the uncertainty in wind power predictions and optimization tools is needed. Prediction of wind speed with time is considered important. Now, the high penetration of wind generation on the electrical system has resulted in increasing the importance of wind speed prediction and its uncertainty. Injection of wind energy in the network has zero operational costs and therefore to be used in its entirety. An imbalance in the production of wind energy can significantly modify the operation of the market, which requires additional power reserves in the system operation. Therefore, new tools are needed to provide reliable information on wind energy production and likely offset imbalances in wind power generation.

The penetration limits of wind energy may lead to severe financial loss to the wind farm owners and discourage future investments in wind energy (Asif and Muneer 2007; Vieira and Ramos 2009). To overcome these problems and to establish wind power as dispatchable electricity generation, the storage of excess wind energy and thereafter use is prerequisite. For this reason, ESSs which are able to recover the excess i.e. not injected wind energy under economically effective terms are widely applied, to achieve maximum exploitation of wind energy at both national and community level applications (WWEA 2014; GWEC 2012; Shafiullah et al. 2013; Ackermann 2005; Islam, Mekhilef, and Saidur 2013; Hedegaard and Meibom 2012; Hessami and Bowly 2011; Hasan et al. 2013; Levine 2007). The wind power growth faces various issues like: operational issues (short and long term balancing, stability in grid network, frequency control, T&D impacts with WPPs, unit commitment, economic dispatch etc.), maintenance issues, network integration issues (reactive power control, voltage control, short circuit power control, flicker control, harmonics control etc.) and environmental issues (physical impacts, flora & fauna, sound propagation, shadows and reflexes etc.). There are also some other issues like availability of grid and capacity, low, medium and high growth rate, new economic incentives, encouraging and favorable wind power policies, reliable wind resource assessments, proper siting and sizing of WPPs (Kaldellis 2004; Ackermann 2005; Schoenung and Hassenzahl 2001).

1.7.1.2.Pumped Storage Development Challenges

Challenges related to pumped storage development may be enumerated as follows:

1.7.1.2.1 Environmental Issues for Storage Siting

Many developers face significant environmental misconceptions about PSP. In the past, almost all PSP projects required construction of at least one dam along the main river which altered the ecology of the river system. Increased awareness of the impacts of large dams and storage reservoirs in the river systems generally preclude further consideration of such large projects, or developers to work directly with the environmental community in order to reduce or mitigate project impacts (DeCesaro and Porter 2009; Renewable Integration 2010; Chaisomphob and Kupakrapinyo 2003; Yang 2011; Rojanamon et al. 2009; Goyal 2007; Feo Edwin 2011; "HDR Data Report" 2010).

Most of the present owners of PSP (typically utilities investor / public developer) attempted to address the ecological impacts during or after construction to improve habitat and provided mitigation measures for specific project. Project proponents today are trying to minimize such problems by focusing on new project sites, in which the proposed construction would have minimal environmental impacts, rather than having measures for post-construction mitigation. A relatively new approach to the development of PSP projects is locating reservoirs in areas that are physically separated from the river systems.

These projects are called "closed loop" pumped storage and have minimal or no impact on river systems. After the initial filling of the reservoirs, the additional requirement of water is minimal operational makeup water that is required to compensate for evaporation and seepage losses. Closed-loop pumped storage systems can be located where the existing river system or other water sources are not available nearby and required to support the grid need (Ingram 2010).

1.7.1.2.2 Regulatory Issues with deployment of Pumped Storage Plants

Another major challenge being faced by the developers of PSP projects is the time required to obtain the license and develop new projects. Throughout the world today, obtaining a license for a new project can take three to five years or more before the project developer can begin construction of the project. Currently there is no alternative approach for obtaining licenses with shorten time period even for the sites of low impact or closed loop (Holttinen et al. 2009). This requires a change in policy. Further a three to five year construction period is very common for such major projects. In addition, the lack of availability of financial institutions to finance such projects in long run is also one of the challenges.

1.7.1.2.3 Existing Market Rules and Impact on Energy Storage Value

With existing energy market rules and the impact on the value of energy storage, pumped storage has the potential to add value through ancillary services, beyond delivery of energy. Lack of energy policy to support the PSP cannot lead to changes in independent system operator (ISO) market rules and definitions of the products that can have a significant impact on the value of ancillary services, including those related to energy storage. Like the Federal Regulatory Energy Commission (FERC) Order 890 and 719, ISO is required to update rates and the market rules so that all non-generating resources, such as demand response and energy storage can fully participate in established markets (Isser 2013). These are usually day ahead and real time market and there are no currents long-term value in a bulk storage project, which can attract investors seeking income security through purchase agreements or long-term energy flows defined value.

1.7.1.2.4 Restriction for Generation and Transmission

Energy storage technologies have the ability to provide components of transmission assets as well as their ability to provide ancillary services and help alleviate congestion by absorbing excess generation. Market rules generally prohibit the transfer of assets from participating in wholesale energy markets and ancillary services to maintain the independence of the network operators and avoiding the possibility of market manipulation, whether real or perceived (Smith et al. 2007; Papaefthimiou et al. 2009; DeCesaro and Porter 2009, “Ancillary services” 2013). Moreover, the policy also prohibits sale of additional services by third party supplier (which may or may not be the wind-PSP) to public utilities those are buying services assistance to meet its obligations to the customers open access. This restriction prevents one of the largest potential markets for the large scale storage which otherwise is useful for wind energy.

1.8 DEREGULATED MARKET

In a vertical integrated power market, electricity is provided to the consumers by public or private utility monopolies. The main aim of such structure is to meet consumer demand and to ensure the reliability of power system (Chirs 2006). The main problem in vertical integrated market is the lack of competition and relatively low improvement in technology. In the electricity market, there is large variation in consumer demand day by day. It is required to improve each sector of power system as well as to increase the transmission capacity rapidly, which is not possible in vertical integrated type market structure. Due to these problems, various electrical utilities switched over to the deregulated market structure. During last decade of 20th century, several countries e.g. U.S., U.K., Spain and Norway started deregulating and privatizing their power market structures, characterized by open competitive energy markets, unbundling electricity services and providing open access to the network (Niimura, Hee-Sang and Ozawa 2002; Chris 2006). Under this structure, vertical integrated market divided into different independent entities and the deregulated market also integrated with other power market, so that different entities compete with each other in order to maximize their profits and consumer get reliable and quality power (Ni and Luh 2002). To establish the competitive market, the generating entities try to improve in their technology as well as generation capacity.

1.8.1. Types of Deregulated Market

The regulated sector is comprised of private or public owned local electricity utilities monopolies, but their tariff, revenues and/or profits are regulated by government appointed independent electricity regulator having quasi-judicial powers. Deregulation is the process by which parts of the regulated sector are opened for competition. The generation sector has generally been open to competition for a long time, and even when the dominant incumbent generator is regulated; generation competition is not usually classed as deregulation. Deregulation begins by a gradual opening of the supply sector to competition in phased manner starting with the very large consumers than small consumers and eventually residential consumers in due course (Schubert et al. 2002). There are range of possible market rules for pumped storage. The PSP may be able to draw desired power at a known fixed price, or required to contract the power purchase in advance. The most advanced market is the Pennsylvania-New-Jersey-Maryland (PJM) market in USA, with location marginal pricing, a form of capacity markets and monetization of ancillary requirements (PJM 2013). This has three key elements –a spot or day-ahead market, ancillary services market and real time market.

1.8.1.1 Spot or Day Ahead Market

The spot or day-ahead market is a forward market in which clearing prices are calculated for each hour of the next operating day based on generation offers, demand bids, bilateral transaction schedules and incremental/decremental bids which are purely financial bids to supply and meet the demand. Day-ahead market enables market participants to purchase and sell energy at binding day ahead nodal prices. It further permits customers to schedule bilateral transactions at binding day ahead congestion charges based on the differences in the marginal price between transaction's source and demand side locations. All spot purchases and sales in the day-ahead market are settled at the day-ahead prices (Chris 2006; PJM 2013).

1.8.1.2 Ancillary Services Market

Ancillary services are needed for the power system to operate reliably. In the regulated industry, ancillary services are bundled with energy. In the restructured power market, ancillary services are mandated to be unbundled from energy (Rau 2001). In general, ancillary services bids submitted by market participants consist of two parts: a bid for capacity and other for energy. Usually, ancillary services bids are cleared in terms of capacity bids. The energy bid represents the participants' willingness to be paid if the energy is actually delivered (Khatod, Pant and Sharma 2009). Different ancillary services in the market may be cleared sequentially or simultaneously. In the sequential approach, market is cleared for the highest quality services first, then the next highest and so on. Four types of ancillary services are traded in sequence i.e regulation, spinning reserve, non-spinning reserve, and replacement reserve which are from the highest to the lowest quality (Pirbazari 2010; Nogales et al. 2002).

1.8.1.3 Real Time Market

To ensure the reliability of power systems, the production and consumption of electric power must be balanced in real-time. The spot market is established to meet the balancing requirement. The real-time balancing market is based on actual real-time operations. Generators that have sold capacity, represent their capacity resources to offer their energy in the day-ahead market (PJM 2013). Any capacity resource must offer its energy in the day-ahead market, regardless of any associated bilateral energy contracts. Available capacity resources that are not selected in the day-ahead scheduling (e.g., the offer price was higher than other generators and therefore the resource was not economically dispatched) may alter their bids for use in the real-time balancing market. If a generator chooses not to alter its bid, its original bid in the day-ahead market remains in effect (Pirbazari 2010; Nogales et al. 2002; Parvania and Fotuhi-Firuzabad 2012).

1.9 WIND-PSP SCHEDULING UNDER DEREGULATED MARKET

Scheduling of wind-PSP generating units is carried out to ensure that consumer side demand is balanced with scheduled bids. It is usually prepared in advance under the deregulated or day ahead market. During this process, the electric system operator seeks to optimize the total generation by minimizing its operating cost to increase overall profit (Guzman 2010). Large amounts of variable wind power generation can cause efficiency losses across the market, because in real time other generating sources would have to be rescheduled and may be operated below their economically optimum level to manage the imbalance between the scheduled and the actual wind generation. In order to reduce these imbalances, the quality of the wind forecast technique is a significant factor to control this impact, because high errors in prediction of wind power can result in high imbalance costs.

The wind forecasting techniques are not accurate at present. Thus, modeling of the uncertainty of predicted wind power generation is a challenging issue for the wind energy producers. To improve the wind operation under deregulated market, maximize the profit and to reduce imbalance, a PSP may be added with wind system (Varkani, Daraeepour and Monsef 2011; "Wind energy- The facts" 2013)

Typically, a reversible pump-turbine is used to pump the water for storage during off-peak hours, so that energy can be stored, later generated and sold to the market during peak hours thus making the generating system economically profitable ("Wind energy- The facts" 2013). Adding PSP to the Wind system can compensate the time-shifting between wind generation and demand to some extent, storing the wind energy that cannot be absorbed by the system during low demand periods and making it available for peak periods using three modes of operation of PSP (generation mode, pump mode and standby mode).

1.10 LITERATURE REVIEW

Many studies have been carried out by earlier researchers for optimal scheduling of Wind-PSP systems (Castronuovo et al. 2004b; Brown et al. 2008; Garcia-Gonzalez et al. 2008; Ummels et al. 2008; Jiang et al. 2012; Pérez-Díaz et al. 2010; Faias et al. 2012; Tsung-Ying 2008; Pappala et al. 2008; Siahkali 2011; Siahkali et al. 20011; Sizhkali and Vakilian 2009; Anagnostopoulos et al. 2005; Xiaoyu et al. 2012; Yan et al. 2011; Li-jie at al. 2012; Bueno et al. 2006; Atwa et al. 2011; Kumar 2013; Po-Hung 2008; Pousinho et al. 2013; Shi et al. 2011; Yu and Rosehart 2012; Zoumas et al. 2004; Viral and Khathod 2012). Many optimization approaches and techniques have been used to analyze the optimal operation of wind-PSP considering the various planning aspects. The planning studies of wind-PSP include resource assessment, penetration level, sizing, generation scheduling and optimal operation methodologies. Integrated operation of wind-hydro requires the knowledge of various aspects such as: concept or technology to be used, number and capacity of the generating units, control, management, scheduling and cost of imbalance etc. The literature reviews carried out under this study has been presented into four broad categories: (i) Energy Storage Systems for Wind power operation, (ii) Scheduling of Wind – PSP System, (iii) Wind-PSP under Deregulated Market and (iv) Risk Management of Wind-PSP System. The brief reviews on these categories are given below:

1.10.1 Energy storage systems for wind power operation

ESSs offer the capability to store generated power by energy systems at instant of low demand and start generating energy at the instant of steep demand. Lot of research work has been reported for practice of energy storage to complement wind power eg.: Swierczynski et al. (2010), Sundararagavan and Baker (2012), Baker and Collinson (1999), Dinglin al. (2012), Hedegaard and Meibom (2012), Ding et al. (2012), Tuohy and O' Malley (2011), Pardron et al. (2011), Beaudin et al. (2010), Ibrahim et al. (2008), McDowall (2006), Electricity Storage Association (2013), Hall and Bain (2008), Ter-

Garzarian (2011), Padimiti and Chowdhury (2007). Many of these publications focused on the advantages and utilization of ESSs advance technologies.

Swierczynski et al. (2010), Sundararagavan and Baker (2012) presented an overview of energy storage technologies with respect to their suitability for Wind Power Plant (WPP). These technologies offer various services e.g. power balancing, load shifting, frequency support and power quality improvement, to both WPP and power system. Paatero et al. (2005) provided the integration of energy storage with the wind power system and effectively reduced the effect of wind power fluctuation by 10%. Baker and Collinson (1999) carried out research in electrical ESS and its influence over electricity retail worldwide. Barton and Infield (2004) developed an easy method based on probabilistic approach to forecast the capability of ESSs for raising the penetration of intermittent embedded renewable generation (ERG) in poor electricity grids and to improve the amount of the electricity output by time-shifting distribution to the electrical network. Tuohy and O'Malley (2011) and Pardron et al. (2011) provided unit commitment model to account the uncertainty in wind power system. This model decreased the wind uncertainty by operating PSP with wind system. Kapsali and Kaldellis (2010) examined the techno-economic viability of a wind-based PSP system, which provided guaranteed energy capacity during the periods of peak demand of an island.

Hedegaard and Meibom (2012) presented a study to categorize the number of ESS technologies viz fuel cells, flow batteries, CAES, batteries etc. considering the time scales necessary for wind power unification. Most of the technologies were found appropriate for providing the power balancing in intra-hour and day-ahead market. Only few were found suitable for seasonal balancing. Benitez et al. (2008) implemented a nonlinear optimization programming based problem to examine the financial and environmental concern for Wind-PSP system. Combined operation of wind-PSP system reduced the CO_2 emissions cost approximately by US $41–$56 per ton of carbon.

The pivotal Unit Commitment and Economic Dispatch (UC-ED) optimization scheme PowrSym3 has been implemented to identify the interests of energy repository for the large penetration of wind output in Netherland power market. Multi criteria optimization model based on heuristic algorithm and Monte Carlo simulation was used to minimize the operating cost in wind and ESS (underground PSP, CAES and heat boiler). For the Dutch system it was concluded that overall CO_2 emission will be more at low wind power penetration (Ummels et al. 2008).

Castronuovo and Pecas (2004a) described an optimization approach to identify the optimal strategy for wind-PSP operation to increase the overall profit. Results of this approach presented near real operation conditions for wind-PSP system. McDowall (2006) implemented a model for stabilizing the wind generation in weak grid by providing the optimum operation of the battery based energy storage devices. The result of this approach provided a rationale for the use of ESSs with several minutes of run time to support high penetrated wind energy. Denholm et al. (2010) provided the integration of ESSs into wind energy system elaborating the market opportunities and various challenges involved in technical and economic issues for these technologies.

1.10.2 Scheduling of Wind-PSP System

Due to uncertain characteristics of the wind, power generated by wind turbines is mostly variable and may affect the power system operation. In order to overcome the effect of variability a joint operation of wind energy system and ESSs technology is required. Among all the ESSs, PSP is the most mature and large capacity system, which can compensate the uncertainties of the wind power optimally. Variable operations of PSP balance the load and generation uncertainty, and thus enhance the ability of power system to incorporate wind power.

Ibrahim et al. (2008) discussed the major technical threats linked with the wind power unification in power system. They also suggested solutions to improve the operation of power generated from the wind and to raise penetration of wind energy in the overall electrical energy generation. Papaefthimiou et al. (2009) discussed the hybrid power system (HPS) consisting of wind, hydro and PSP. HPS results in a significant increase of renewable energy penetration and efficiently utilize the wind and hydro potential to provide firm capacity to an Island power demand, replacing expensive peak units. Dinglin et al. (2012) and Duque et al. (2011) developed an economical wind-PSP model to minimize the market imbalances due to the anxiety in the wind power prediction and in the market costs. With this model, the utilities may reduce the operational risk and fully avoid the imbalances in the wind power production by the operation of PSP. Caralis et al. (2010) presented a methodology for the initial design and cost estimation of the wind power system (WPS).

Bessa et al. (2012) discussed three possible heuristic strategies for managing the wind-hydro system during the operational day according to day-ahead optimized strategy. A chance-constrained based optimization algorithm covering wind power uncertainty was also described by them. The operational strategies showed good performance without significant decrease of the actual profit compared to the expected profit (i.e. profit computed during the day-ahead optimization phase). Nguyen Ngoc et al. (2009) formulated a deterministic problem using linear programming method to provide the optimal operation for wind system. In this method, the hydraulic storage was utilized to increase the value of wind power by minimizing the intermittences and fluctuations in the power generation from wind resources. Mendes et al. (2010) and Caralis et al. (2012) analyzed the technical feasibility of PSP by considering three different scenarios of wind-photovoltaic integration. The results obtained show that the parallel development of variable operation of PSP reduced the significant amount of unutilized wind energy.

Angarita and Usaola (2007) suggested two different strategies for maximizing the revenue of a wind generation company (WGENCO) and utilized the SIPREOLOCO tool for predicting the wind power to get the optimal bid of WGENCO and maximized the whole revenue by providing the combined operation of wind and hydropower system. The considered wind-hydro system resulted in increase of overall saving by 46% as compared to separate operations. Shahidehpour and Khodayar (2012) proposed a coordination methodology for wind and PSP system in day ahead market subjected to various transmission security constraints. The result of this approach shows that the operation of PSP reduces the operation cost and the transmission congestion across the wind system under day ahead market.

Castronuovo and Lopes (2004a) proposed a short term scheduling of wind and PSP system in day-ahead market considering the effect of wind uncertainty, where combined operation of wind-PSP system increased the operational profit by 13% as compared to the separate wind system operation. Castronuovo et al. (2004b), proposed an hourly-discretized optimization algorithm (i.e. LP and IPM) to recognize the optimal day-to-day functional scheme to be pursued by the pumping machineries and the wind turbines. The Monte Carlo simulations (wind-power time-series scenarios) was applied for the intermittent nature of wind and wind power forecast employing a time series, for a time prospective of 48 hours, in an independent peninsula to increase the profit. The authors provided best bidding strategy for wind-PSP system without considering the risk of wind uncertainty. Brown et al. (2008) minimized the operating cost using LP with CLP solver for an island. Fuzzy clustering algorithm was used for wind-PSP scheduling and dynamic security criteria were considered without risk assessment.

The interim optimum working of an electric network encompassing various thermal generating units and a PSP was examined to draw consequences around the improvement of PSP to system recurring expenses for an island by Pérez-Díaz et al. (2010). In order to decrease the total generation expenses of the system, mixed integer linear programming (MILP) was applied to get the optimum hourly working of thermal, hydro and PSP,

Siahkali (2011) acquainted particle swarm optimization (PSO) to figure out the wind generation scheduling difficulties, incorporating reserve requirement, load generation balance and wind generation constraints. The proposed method was tested on

PSP to revise the uncertainties of wind power output and other parameters in electrical networks. The approach was in the good agreement for optimal scheduling and provided the best trade-off between the cost and constraints, though the wind uncertainties were ignored. Siahkali et al. (2009) solved MINLP problem using PSO and the Global Variant-Based Passive Congregation (GPAC) to generate faster and near optimal schedule compared to the conventional PSO. The hybrid technique (GPAC-PSO) did not provide accurate results as were obtained using PSO.

Anagnostopoulos et al. (2005) presented an evolutionary algorithms (EA) based numerical methodology to solve single as well as multiobjective optimization problem for optimal sizing of the different components of a reversible hydraulic system i.e. PSP, designed to retrieve the electrical power injected from wind energy farms due to grid restriction. The results suggested that a robust advanced design can be crucial for the economic and technical feasibility of the system. Xiaoyu et al. (2012) described a hybrid system using PSP for reducing the impact of wind power and to transfer energy from low to high demand periods. A genetic algorithm (GA) based multiobjective optimization problem was solved under the economic and security criteria of the grid. The result of the optimization problem showed that optimal system has the characteristics of the LPSP (loss of power supply probability) which is almost zero and the lowest CUE (cost of unit energy). Yan et al. (2011) used an improved GA to solve the MILP problem of a hybrid PSP-wind-solar power system in autonomous power system. This optimization model used wind and solar reserve adequately and improved the system stability.

Bakos (2002), Matevosyan (2008), Khatod et al. (2009) and Jaramillo et al. (2004) provided the combined operation of wind hydro system and drawn general conclusions on the benefits and the limitations of the joint operation as well as evaluated some areas in which further research is required.

1.10.3 Wind-PSP Under Deregulated Market

In the electricity market, there is large variation in consumer demand day by day. To overcome the difficulties in meeting the needs of large variation, various electrical utilities switch towards the deregulated market structure. Ni and Luh (2002) reported that in deregulated market structure, vertical integrated markets were divided into different independent entities and were integrated with other power markets. These different entities should compete with each other to maximize their profits, where every entity or player tries their best to be in competition by optimizing their operation in efficient way. Kannan et al. (2010) used this model to analyze the various dynamic and static impact of the system on the market under uncertain condition. Migliavacca et al. (2006) used game theoretical model to analyze the effect of market competition for providing the long term simulation. Different game theory based models have been used for designing the optimal bidding strategy under the electricity market (Migliavacca (2006), Song (2002), Ceppi (2010), Ming et al. (2010), Mazadi et al. (2013), Karangelos et al. (2011)).

Jiang et al. (2012) developed a powerful optimization model to entertain wind generation anxiety with the goal of affording a strong unit commitment programme for the thermal generators in day-ahead market that diminish the overall cost covering the inferior wind output plan.

Pappala et al. (2008) addressed an effective PSO methodology for functioning of thermal, nuclear, wind-PSP units considering the demand and wind output uncertainty in a day-ahead market and also reduced the stochastic error during wind forecasting. Li-jie et al. (2012) modeled the PSP and wind farm operation using scenarios based fuzzy clustering technique and found that the mixed dividend of wind field can be enriched by appropriate sizing and siting of the PSP station. However, the authors did not consider the effect of wind uncertainty.

Niimura et al. (2002) applied a fuzzy reversion model to evaluate the unpredictable electricity market expenses in deregulated market. The unpredictable electricity market expenses are computed by an autoregressive model with the help of artificial neural network (ANN). Rong-Ceng (2008) developed a mathematic model to scrutinize the economic aspects of the ESSs in deregulated market. Energy costs, O&M costs transmission delivery prices, longer duration of the expenditure on equipment, expenses on ESSs are the main issues in the above said model. For evaluation of expenses of electricity in spot market, Mirsaeidi et al. (2012) provided an electric load regulation approach to introduce Siah Bishe PSP in Iran power system and evaluated it from the operational and technical consideration. Liu B. et al. (2006) developed a model to deal with uncertainty that minimized the total purchase cost to obtain an excellent day-ahead plan. Hooke and Jeeves pattern search along with Monte Carlo simulation algorithm has been examined to figure out the above model. Contreras et al. (2001) introduced a simulator model to analyze various sell-off models available in the market.

Parvania and Fotuhi-Firuzabad (2012) recommended a demand response (DR) scheme that assists the wind power by alteration system load. Durrwachter and Looney (2012) observed the market principles enforced within the Electric Reliability Council of Texas along with zonal and nodal market associated with wind generation. Dukpa et al. (2010) presented a novel optimum sharing procedure for a wind energy generation (WEG) to use energy storage tool for engaging Day-Ahead Commitment Process (DACP).

Garcia-Gonzalez et al. (2008) investigated the combined operation of a wind farm and a pumped-storage for profit maximization for the generation company. The Mixed Integer Linear Programming (MILP) using CPLEX solver with two random variables: (i) market expenses and (ii) wind output, was used to solve the proposed two-stage stochastic programming problem. To analyze and forecast the electricity prices, Input Output Hidden Markov Model (IOHMM) approach was applied to generate different electricity price scenarios in a day-ahead market and was useful for investment decision about new PSP. Khodayar et al. (2013) optimized wind and PSP generation with a stochastic SCUC (security-constrained unit commitment) model through several coordination strategies.

The evaluation of the proposed method was based on the total operation cost, wind energy uncertainty and the corrective action cost.

1.10.4 Risk Management of Wind-PSP System

Due to wind variability and to maintain the security and safety to the market operation, it is required to perform the risk analysis (Hosseini-Firouz 2013; Moghaddam et al. 2013). Ming et al. (2010) provided the risk assessment on the seaward wind field consisting of various steps like risk determination, risk evaluation and the risk allocation. Duque et al. (2011) acquainted hydro-pump system in an electricity market to minimize imbalance as well as reduced the risk due to the uncertainty in wind power prediction and in prices of the reserve market. Ni and Luh (2002) introduced a stochastic mixed integer optimization model to perform the bidding strategies to optimize bids for both energy and reserve markets under a deregulated market. The mean-variance method is applied to manage bidding risks, where a risk penalty term related to MCP and reserve price variances is added to the objective function. An optimization based algorithm combining Lagrangian relaxation and stochastic dynamic programming is presented that can significantly reduce profit variances and thus reduce bidding risks. Dukpa et al. (2010) proposed a multiobjective MILP type problem that employs WEG and an energy storage device (ESD) for participating in the day-ahead market. The WEG is modelled to function as a price-taker. The objective of the proposed formulation is to maximize returns from the market considering the best forecast as well as to minimize risks considering the forecast uncertainties.

Botterud et al. (2012) developed a recent model for ideal sales of wind energy in day-ahead electricity merchandise with uncertainty in wind cost and power. This approach determines the agreement tool in markets with locational marginal pricing (LMP); where wind energy is not automatically penalized from change between day-ahead plan and real-time dispatch. Utility theory and Conditional Value At Risk (CVAR) are applied to perform the danger inclination of the wind power operators.

Game theory based Nash equilibrium technique was used by Mazadi et al. (2013) and Karangelos et al. (2011), which effectively controlled the risk and attained highest benefits but did not perform any uncertainty related risk analysis. A GA based game-theoretical model has been implemented in order to determine the best bidding scenario for a generation utility envisaging wind units as a price taker in day-ahead power market (Sarkhosh et al. 2011).

To apply the risk management strategies on the Wind-PSP system, Taguchi technique can be a promising technique. As per Taguchi's method, the choice of a "top-up" or a "bottom-up" approach depends on the different phase of the product i.e. design and production phase. To reduce the variation in design variables, a Taguchi method based experimental design technique has improved the quality for achieving the consistency in performance (Nataraj et al. 2006, Taguchi 1987, Ross 1988; Kackar 1985; Liu D. 2005; Sheng-Ju et al. 2009; Wei-Chung et al. 2007).

1.11 RESEARCH GAPS

Based on the literature review, the following research gaps in the subject area of Wind-PSP were observed:

(i) Efficient bidding strategy for operating wind-PSP to increase the profit in day-ahead or spot market.

(ii) The combined operation of wind-PSP to reduce the market imbalance that may be created by the wind power plant alone.

(iii) Use of variable speed type PSP unit to reduce market imbalances as well as to increase the flexibility of the operation of Wind-PSP system.

(iv) The short term scheduling of wind-PSP by considering the wind data uncertainty.

(v) Forecasting of wind speed data not being very accurate brings the risk in the system, thus requiring proper management of the risk for the stable operation of wind-PSP system.

1.12 OBJECTIVES OF RESEARCH WORK

Keeping in view the research gaps in the subject areas, the present study has been carried out for scheduling of wind-pumped storage plant under day-ahead market with the following objectives:

(i) To increase the day-ahead market profit by limiting the active power output variations of wind energy resources, considering the needs of grid and stored energy available in PSP.

(ii) To reduce the market imbalance due to the uncertainty in forecasted wind data as well as to increase the overall profit across the system.

(iii) To determine and manage the uncertainty risk for the stable operation of the wind-PSP system.

(iv) To minimize the effect of uncertainty risk of wind-PSP system under the worst conditions.

1.13 AUTHOR'S CONTRIBUTION

A twenty four (24) hours time frame has been considered under this study for the hourly scheduling of wind-PSP under day-ahead market, where wind and PSP are operated as a single entity, but not necessarily installed at the same or adjacent location. PSP consists of reversible turbine unit which can either generate electricity or pump the water to storage as per requirement. Both the systems (wind and PSP) are connected with the grid. An optimal strategy has been developed to efficiently utilize the power generated by wind and PSP as per the demand or bid received from the electricity market.

A mixed integer type problem has been formulated for providing the scheduling of wind-PSP system. The objective of the problem is to determine the optimal hourly scheduling of wind – pumped storage energy by maximizing the profit as well as reducing the market imbalance created by the variation of wind energy. For day-ahead power market, wind energy has been forecasted. The imbalance in forecasted energy and market demand is reduced by using variable speed types units in both generating and pumping modes. The optimal solution has been obtained by considering four different cases.

Uncertainties in the electricity market always affect the scheduling of wind-PSP system. These uncertainties present in the system are in the form of price, demand and generation. In the present study, stochastic approach has been used to implement the wind-PSP scheduling problem considering the wind system uncertainty as input data for maximizing the overall profit. A probability based forecasting model has been used to forecast the uncertainty in the input data and the probability distribution function for the each set of input data were computed. Three cases have been studied to check the optimality of the solution.

Probabilistic forecasting technique is used to predict the wind uncertainty that bring risks in the system. An experimental design technique based on Taguchi method is employed to calculate and manage the uncertainty risk in this study. Orthogonal array structure is used to select the best level of scenarios on the basis of maximum risk. An variable speed type PSP unit has been considered to reduce the market imbalances caused by uncertainties in wind generation and market demand.

In order to reduce the effect of uncertainty during wind-PSP scheduling, a game theory based Min-Max optimization method has been developed. The solution of this study provided the worst case performance of the system under uncertain conditions. The nominal scenario and the worst-case scenario have been considered using the concepts of min-max optimization.

1.14 ORGANIZATION OF THE THESIS

The present thesis has been organized into six chapters and the work included in each chapter has been presented in the following sequence

Chapter-1, gives an overview of global energy scenarios, wind energy, energy storage system and it also covers the basics of Wind and PSP system, benefits of PSP for providing the integration with wind system, challenges and opportunities involved with Wind-PSP system. Literature review on the scheduling of Wind-PSP, operation of Wind-PSP under deregulated market and risk management of Wind-PSP system has been presented leading to identification of gaps in the knowledge and objectives of this research study.

Chapter-2, presents the mathematical formulation for optimal scheduling of wind-PSP system as mixed integer type problem in order to maximize the overall profit.

Chapter-3, describes the stochastic approach for wind-PSP scheduling by considering the effect of wind data uncertainty under day-ahead market.

Chapter-4, presents the Taguchi method based mathematical approach to manage the risk across wind-PSP system by providing the system scheduling for the selected set of scenarios generated after number of experiments and having the maximum risk across wind-PSP system.

Chapter-5, presents a new approach to manage the risk across wind-PSP system, deals with the game theory based min-max approach to consider the effect of wind data uncertainty across wind-PSP system.

Chapter-6, summarizes the conclusion of the research work carried out using different approach/methodology and presents the suggestions for future work.

CHAPTER–2

WIND-PSP GENERATION SCHEDULING UNDER DAY-AHEAD MARKET

2.1 INTRODUCTION

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

Contaxis and Kabouris (1991) presented a method for the short term scheduling of wind–diesel energy system by using ARIMA model to predict the load and wind energy. To predict the performance of wind-diesel energy systems, Dokopoulos et al. (1996) developed a Monto Carlo method based unit commitment problem with the objective of minimizing the operating cost of wind-diesel system. This method predicted the performance and reliability of Wind-Diesel energy system successfully.

Chen (2008) provided a scheduling method to minimize the total operating cost of the wind-thermal system by using the hybrid dynamic programming. Special reserve constraints were incorporated in scheduling problem to operate the system within the required stability margin.

Integration of wind and energy storage device is necessary to utilize the full potential benefits and reducing the impact of uncertainty in 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, flywheels etc., for minimizing the impact of wind energy.

Tanabe et al. (2008) has developed a forecasting technique for the scheduling of wind power generation and used the battery as an energy storage device 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. For the wind farms of large size, PSP is one of the economically viable and technically mature alternative for energy storage (Daim et al. 2011).

For the conventional fixed speed type PSP, it is not possible to adjust the input power during the pumping mode. However, with the recent development in the PSP technology, adjustable speed type units have been developed with the possibility to change the input speed during the pumping. It not only improves the power system reliability but also enhances the competitiveness in the day-ahead market. Lidgate et al. (1982) used the heuristic technique to schedule the pumped storage and thermal plant for every half an hour interval and provided the comparison of the pumping cost with other alternative methods of frequency control.

In traditional systems fuel cost of hydrothermal has been reduced by operating the pumped-storage generators during the peak demand and pumped the water back into the upper reservoir during the low demand (Xiaohong et al. 1994, Xiaohong et al. 1997). Castronuovo and Lopes (2004a) described an hourly-discretized optimization algorithm, aiming to identify the optimum daily operational strategy to smoothen the operational power generation changes that were due to the natural wind-power fluctuations. Thus, the output power is kept within upper and lower limits with the help of PSP. To achieve the maximum profit, various optimal bidding strategies have been developed for a PSP by providing the variation in PSP operation under the competitive market (Ning et al. 2004, Kanakasabapathy and Swarup 2008; 2010).

Caralis et al. (2012) provided the combined operation of wind energy with PSP system by converting unutilized wind energy into water storage. Anagnostopoulos et al. (2007) studied the variable speed operation of separate pump and turbine unit to provide flexibility in PSP operation. This variable speed operation utilized the large quantity of wind energy.

2.2 OPERATION OF WIND POWER PLANT

Wind turbine is used to convert the kinetic energy of the moving wind into mechanical energy with the help of a rotor consisting of hub and blades (Earnest and Wizelius 2011). The kinetic energy of the wind *(E_k)* is expressed as per Eq. (2.1).

$$E_k = \frac{1}{2} \times m \times V^2 \tag{2.1}$$

where, m is the mass of moving air and V is the air velocity. The mass of wind also changes with change in the wind velocity and can be defined as per Eq. (2.2).

$$m = \rho \times V \times A \times t \tag{2.2}$$

where, ρ is the wind density, V is the velocity of air, A is the swept area of blades and t is the time deviation. Therefore the total energy *(E_k)* and the power *(P_k)* across the wind turbine rotor are defined using the Eq. (2.3) and (2.4) respectively.

$$E_k = \frac{1}{2} \times \rho \times A \times V^3 \times t \quad (Joules) \tag{2.3}$$

$$P_k = \frac{1}{2} \times \rho \times A \times V^3 \qquad (Watt) \tag{2.4}$$

The wind turbine converts the power of moving air into the mechanical power, which result in a reduced speed in the air mass. The theoretical optimum power as the output of the wind turbine is given by Eq. (2.5).

$$P_m = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \quad (Watts) \tag{2.5}$$

where, C_p is the Betz constant. The wind turbine is coupled with electrical generator to convert the mechanical power (P_m) into electrical power (P_e) and supply to the power grid as given in Eq. (2.6), where η_m is the mechanical efficiency and η_e is the efficiency of electrical generator.

$$Pe = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \times \eta_m \times \eta_e \quad (2.6)$$

2.3 OPERATION OF PUMPED STORAGE PLANT

The operation of PSP is very much similar to the conventional hydro power plant. The power generated by PSP in the generating mode P_{gen}, depends on the rate of flow of water q_t, from upper to lower reservoir and head *'h'* (level difference between upper and lower reservoir). η_h is the efficiency of PSP in generating mode as given in Eq. (2.7).

$$P_{gen} = g \times q_t \times h \times \eta_h \quad (2.7)$$

In the pumping mode, P_{pump} is the power consumed by the PSP for pumping the water from lower to upper reservoir, as given by Eq. (2.8), where η_p is the efficiency of PSP in pumping mode.

$$P_{pump} = \frac{g \times q_p \times h}{\eta_p} \quad (2.8)$$

where, g is the gravitational constant and q_p is the amount of water pumped by PSP.

The water storage in upper reservoir for the PSP is given by the Eq. (2.9), where V_t and V_{t+1} are the volume of water stored in upper reservoir during t^{th} and $(t+1)^{th}$ time respectively. Water inflow and reservoir spillage have been neglected in this equation.

$$V_{t+1} = V_t + q_p - q_t \quad (2.9)$$

In the deregulated market, PSPs are the most commonly used ESS. The energy equation for PSP has been derived as Eq. (2.10) by substituting q_t and q_p from the Eq. (2.7) and (2.8) in the Eq. (2.9).

$$\left(V_{t+1}-V_t\right)\times h\times g=\left(P_{pump}\times n_p-\frac{P_{gen}}{n_h}\right) \tag{2.10}$$

By multiply time interval Δt on both sides of Eq. (2.10), we get

$$\left(P_{t+1}-P_t\right)\times \Delta t=\left(P_{pump}\times n_p-\frac{P_{gen}}{n_h}\right)\times \Delta t \tag{2.11}$$

$$E_{t+1}=E_t+\left(P_{pump}\times n_p-\frac{P_{gen}}{n_h}\right)\times \Delta t \tag{2.12}$$

where P_t and E_t are the power and the energy, stored in the PSP reservoir respectively at t^{th} time.

2.4 WIND-PSP SCHEDULING UNDER DAY AHEAD MARKET

In the present study, wind energy has been forecasted for day-ahead power market and the imbalance between the forecasted energy and market demand were reduced by providing the variable speed of PSP in both generating and pumping modes. To maintain the efficiency during the pumping mode, adjustable speed type unit is used which operates at different speeds by changing its synchronous speed using the technique of power electronics based frequency converter.

The wind and pumped storage scheduling problem is formulated as a mixed integer nonlinear programming (MINLP) problem and the optimal solution has been obtained by considering four cases. In the first case (Case-I), only wind farm has been considered to supply the power under the day-ahead market and attempted to increase the overall profit. In the second case (Case-II), the combined operation of wind-PSP system has been used, where the PSP operate at fixed speed during pumping mode. In the third case (Case-III), pumping is done at two different speeds, whereas in the fourth case (Case-IV) variable speed operation has been provided, which further reduced the market imbalances created by the wind energy.

2.4.1 Objective Function

The objective function has been formulated to maximize the total revenue obtained from the combined operation of wind power plant and PSP as presented in Eq. (2.13). This objective function consists of the revenue of pump storage plant $R_{psp}(t)$ as well as wind power plant $R_{wind}(t)$ and the revenue loss due to the power imbalances $R_{loss}(t)$ caused by the wind power plant.

Maximize: $$\sum_{t=0}^{T}\left(R_{psp}(t)+R_{wind}(t)-R_{loss}(t)\right) \tag{2.13}$$

Where:

$$R_{psp}(t)=R_{gen}(t)-R_{pump}(t) \tag{2.14}$$

$$R_{gen}(t)=s(t)\times P_{gen}(t)\times \lambda_{mkt}(t) \tag{2.15}$$

$$R_{pump}(t)=Pw_{pump}(t)\times \lambda_{wind} \tag{2.16}$$

$$R_{wind}(t)=Pw_{mkt}(t)\times \lambda_{mkt} \tag{2.17}$$

$$R_{loss}(t)=\omega\times \lambda_{mkt}(t)\times[P_d(t)-Pw_{mkt}(t)-s(t)\times P_{gen}(t)] \tag{2.18}$$

The Eq. (2.14) determines the total revenue of pump storage plant at t^{th} hour, where $R_{gen}(t)$ is the revenue of the PSP during generating mode and $R_{pump}(t)$ is the revenue loss of PSP during pumping mode. In Eq. (2.15), $P_{gen}(t)$ is the power generated by the pump storage plant during generating mode. $\lambda_{mkt}(t)$ is the market price of energy at t^{th} hour. The total revenue loss during the pumping mode $R_{pump}(t)$ is the product of the power drawn from wind power plant generation and the wind power price as given in Eq. (2.16), where $\lambda_{wind}(t)$ is the price paid by the PSP to the market for utilizing the wind power for pumping operation and considered constant for the whole period. $R_{wind}(t)$ is the revenue from the power supplied by wind plant $Pw_{mkt}(t)$ at t^{th} hour as shown in Eq. (2.17). $R_{loss}(t)$ is the revenue loss or the penalty imposed by the market for creating imbalance between generation and market demand ($P_d(t)$) as given in Eq. (2.18). ω is the penalty factor, whose value is taken constant for all the period.

2.4.2 Control Variables

A control variable *s(t)* is used in this problem formulation to control the operation of PSP in generating mode as given in Eq. (2.19). Whereas $sp_a(t)$ and $sp_b(t)$ are to control the operation of PSP in pumping mode as given in Eq. (2.20) to (2.21).

$$s(t) \in \{0,1\} \tag{2.19}$$

$$sp_a(t) \in \{0,1\} \tag{2.20}$$

$$sp_b(t) \in \{0,1\} \tag{2.21}$$

2.4.3 Constraints

Above objective function has been formulated subjected to the following equality and inequality constraints:

2.4.3.1 Energy Balance Constraints

The Eq. (2.22) to (2.24) determines the energy balance in the upper reservoir for different cases as shown in Fig. 2.1.

For Case I No PSP is used

For Case II

$$E(t+1) = \left(\eta_p \times sp_a(t) \times P_p^{\max} - \frac{s(t) \times P_{gen}(t)}{\eta_h} \right) \times t + E(t) \tag{2.22}$$

For Case III

$$E(t+1) = \left(\eta_p \times sp_a(t) \times P_p^{\max} + \eta_p \times sp_b(t) \times P_p^{\min} - \frac{s(t) \times P_{gen}(t)}{\eta_h} \right) \times t + E(t) \tag{2.23}$$

For Case IV

$$E(t) = \left(\eta_p \times sp_a(t) \times Pp(t) - \frac{s(t) \times P_{gen}(t)}{\eta_h} \right) \times t + E(t) \tag{2.24}$$

At the beginning of $(t+1)^{th}$ hour the energy in the reservoir *E(t+1)* is the sum of initial level in the reservoir *E(t)* at t^{th} hour.

$\left(\eta_p \times sp_a(t) \times P_p^{\max}\right)$, $\left(\eta_p \times sp_a(t) \times P_p^{\max} + \eta_p \times sp_b(t) \times P_p^{\min}\right)$ and $\left(\eta_p \times sp_a(t) \times Pp(t)\right)$ are the energy supplied to the reservoir during pumping mode for Case-II, Case-III and Case-IV respectively.

$\left(s(t) \times P_{gen}(t)\right)/\eta_h$ is the energy used from the reservoir during generating mode, whereas *s(t)*, $sp_a(t)$ and $sp_b(t)$ are the a control variables. η_p and η_h are the efficiency of pumped storage plant during pumping and generating mode respectively.

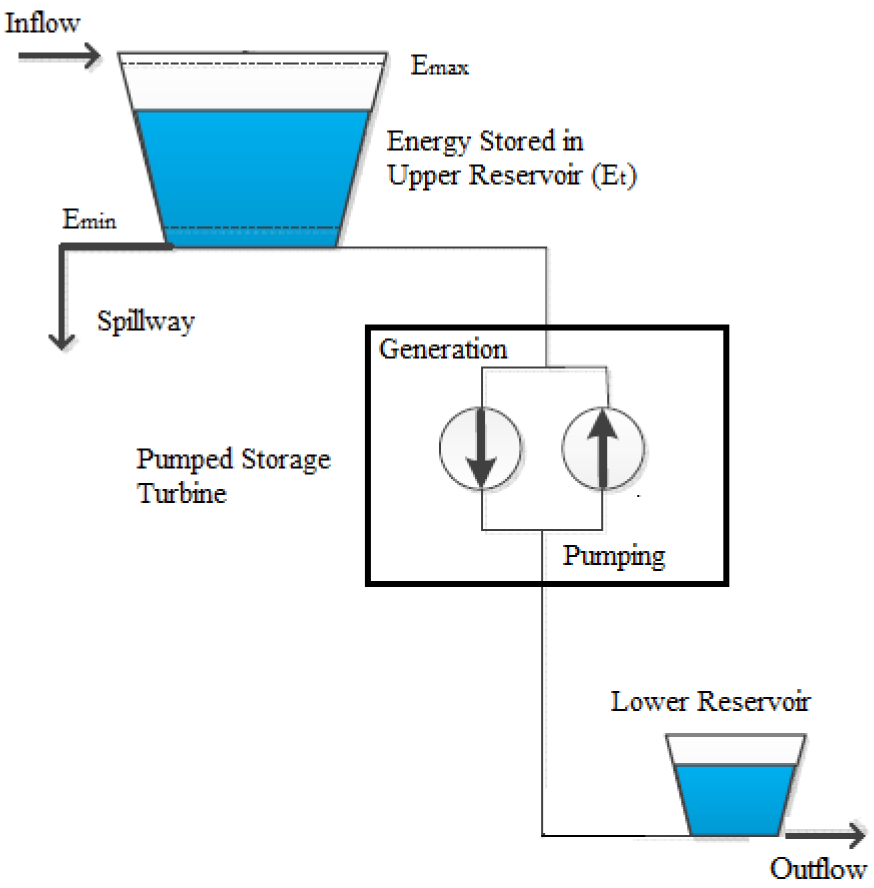


Fig. 2.1: Pumped Storage Plant Model

2.4.3.2 Pumping Constraint

For the pumping operation, the PSP can take the power from the wind power plant. For each case, different type of pumping operations have been provided as defined in the Eq. (2.25) to (2.27).

For Case II

$$Pp_{\max} \times sp_a(t) = Pw_{pump}(t) \tag{2.25}$$

For Case III

$$Pp_{\max} \times sp_a(t) + Pp_{\min} \times sp_b(t) = Pw_{pump}(t) \tag{2.26}$$

For Case IV

$$Pp(t) \times sp_a(t) = Pw_{pump}(t) \tag{2.27}$$

2.4.3.3 Imbalance Constraint

In Eq. (2.28), $R_{loss}(t)$ represents the total imbalance in the market, which implied that the total generation provided by the market is always equal to or less than the total demand across the market, to avoid the over generation of power in the market.

$$R_{loss}(t) \geq 0 \tag{2.28}$$

2.4.3.4 Reservoir Limit

The energy stored in the upper reservoir has upper and lower limits as given in Eq. (2.29).

$$E_{\min} \leq E(t) \leq E_{\max} \tag{2.29}$$

where, E_{min} and E_{max} are the minimum and maximum energy level in the upper reservoir.

2.4.3.5 Reservoir level

In this formulation, it is assumed that the initial and final levels of the reservoir are equal at the beginning and end of the time T so that stored energy can be utilized in future for scheduling as shown in Eq. (2.30).

$$E_0 = E_T \tag{2.30}$$

where, E_0 is the initial level of reservoir and E_T is the final level of the reservoir.

2.4.3.6 Generation Limit

This constraint keeps the power generated by PSP with in the upper and lower limits as given in Eq. (2.31).

$$P_{gen}^{\min} \le P_{gen}(t) \le P_{gen}^{\max} \tag{2.31}$$

where, the $P_{gen}^{\min}$ and $P_{gen}^{\max}$ are the minimum and maximum power generation limits of PSP.

2.4.3.7 Pumping Limit

This constraint is the power consumed by the PSP (in pumping mode) with the upper and lower limits as given in Eq. (2.32).

$$P_p^{\min} \le Pp(t) \le P_p^{\max} \tag{2.32}$$

where, the $P_p^{\min}$ and $P_p^{\max}$ are the minimum and maximum pumping limits of PSP.

2.4.3.8 Switching Constraint

These constraints control the operation of PSP between the generating and pumping mode and do not allow both the operation at the same time as given in Eq. (2.33).

$$s(t) + sp_a(t) + sp_b(t) \le 1 \tag{2.33}$$

2.5 SOLUTION TECHNIQUE

In this study, MINLP problem is formulated using AMPL software with KNITRO as a main solver (AMPL (2011)). This solver is mainly used for finding local solutions of different types of optimization problem with or without constraints. It provides the efficient and robust solution of small or large problem. The KNITRO mixed integer programming (MIP) code offers two algorithms for Mixed-Integer Nonlinear Programming (MINLP). The first is a nonlinear branch and bound method and the second implements the hybrid Quesada-Grossman method for convex MINLP. The KNITRO MINLP code is designed for convex mixed integer non-linear programming and is a heuristic for non-convex problems. For this problem, convex MINLP is using a nonlinear branch and bound method to find the optimal solution.

2.5.1 Branch and Bound Method

The general paradigm of Branch-and-Bound (B&B) deals with optimization problems over a search space that can be presented as the node based search tree and is shown as Fig. 2.2. In the simplest form of the algorithm, the search tree traversed in some order and the kept the score of the best nodes as a bound.

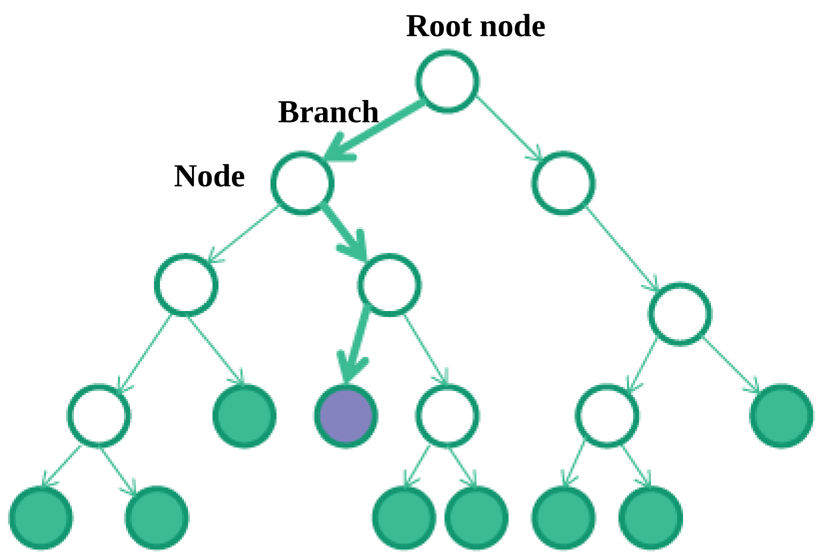


Fig. 2.2: Node based search tree

Whenever a node is reached, whose score is worse than B, the search tree is terminated at that node, i.e., its subset will not be searched, since it is guaranteed not to contain a node with a score better than current best bound. The algorithm can be improved by using some other method to come up with a relatively good candidate, which will yield a good bound before the search has even begun. It is also possible to improve the traversal order heuristically. The tree search algorithm for branch and bound method used in the problem as given by section 2.5.2 and the flowchart for the algorithm is presented as Fig. 2.3.

2.5.2 Branch and Bound Algorithm

i. **Initialization** – Select the MINL problem and initialize the lower f_L bound of variable with (-ve) infinite value.

ii. **Upper bounding** – Solve the nonlinear relaxation method of the problem by satisfying all constraints defined above. If its upper bound value f_U' is less than the current value than update the bound variable by setting $f_U = f_U'$. If node has a lower bound to the optimum, set f_L to this, otherwise f_L is equal to (-ve) infinity.

iii. **Branching –** Found the other most promising node by branching the single node into other similar nodes with best upper bound value as compared to f_U.

iv. **Lower Bounding –** Bound the optimum value for each node. If any of the new lower bounds are higher than f_L then set f_L to maximum of these lower bounds.

v. **Convergence test** – If any of the node has the value lower than the current value, then return to Step 2, so that the node will be branched further.

vi. **Termination –** At any time during this process, if the node becomes infeasible (at $f_U < f_U'$), delete the solution nodes or sub problem. This process is performed until there are no more active nodes and the optimal solution has been found.

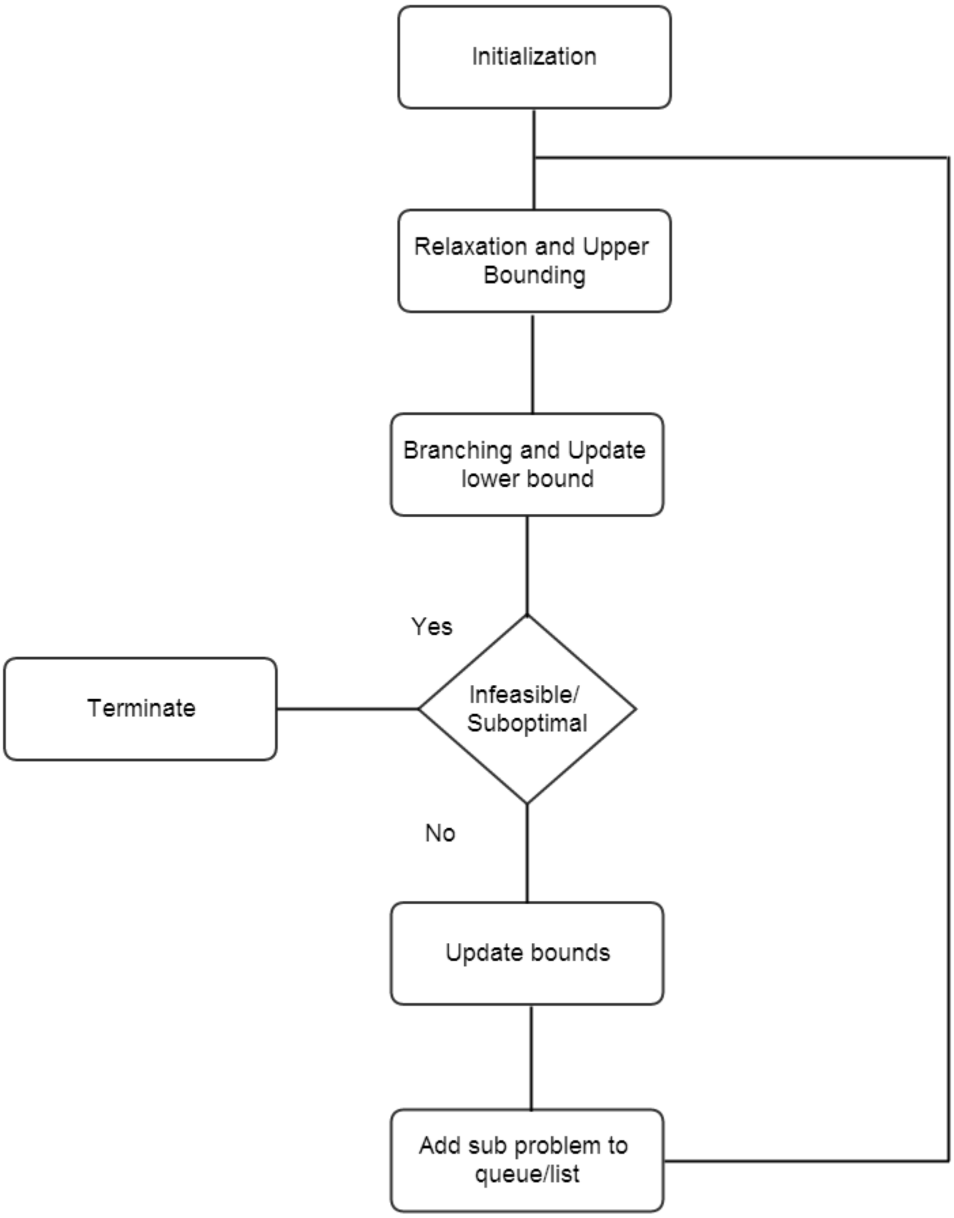


Fig. 2.3: Branch and bound flow chart

2.6 RESULTS AND DISCUSSIONS

Four different cases have been considered to reduce the imbalances across the deregulated market using the hourly wind data for a day. PSP and reservoir data used for all the four cases have been presented in the Table 2.1 and Table 2.2 respectively. Fig. 2.4 to 2.14 present the results of scheduling for all four cases obtained with AMPL using the KNITRO as an optimization solver. In all the cases, pumping operation has been provided in such a way that it kept the initial reservoir level equal to the final level at the end of wind-PSP scheduling as shown in Fig 2.7, 2.10 and 2.13. Table 2.3 presents the results obtained from all the four cases.

In Case-I, only wind farm is used to supply the market demand. From Fig. 2.4, the change in the generation and demand can be seen, where the wind farm supply the maximum output to the market in order to reduce market imbalance. The maximum revenue loss occurred between hours 9 and 15, when the market price is at peak. On the other hand, there is lot of overproduction of wind power between hours 18 and 22, which did not provide any contribution to the revenue losses and remain unutilized. From Table 2.3, it is seen that the overall profit of wind farm is *Rs.*[*] 1435.73 thousand and the revenue loss is nearly *Rs.* 490.31 thousand, which is approximately 25% of the total revenue. In order to reduce these revenue losses, it is required to store the unutilized wind power by using PSP as analyzed in Case-II, Case-III and Case IV.

Table 2.1: Pumped Storage Plant Data

Mode of Operation	Efficiency %	Rated Power, MW	
		Maximum Limit	Minimum Limit
Generation Mode	83.3	59.65	0
Pumping Mode	90.0	76.06	46.00

Table 2.2: Reservoir Data

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

Table 2.3: Result of Wind and Pumped Storage Plant Operation

Type	Profit (thousand Rs)	Revenue Loss (thousand Rs)	Total Generation (MWh)	Total Pumping (MWh)
Case-I	1435.73	490.31	0	0
Case-II	1777.08	199.53	242.05	304.24
Case-III	1831.11	145.12	291.33	366.18
Case-IV	1834.14	144.21	292.28	367.37

[*] *Rs* – Indian Rupees 1 US $ = 60 *Rs* (August 2014)

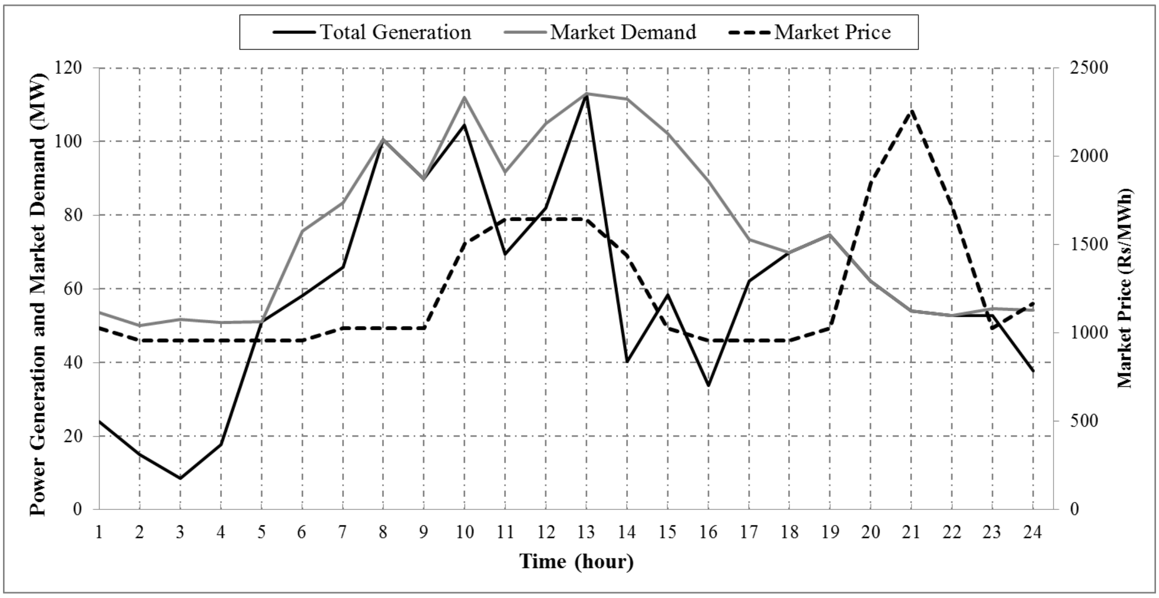


Fig. 2.4: Wind Farm System Operation (Case-I)

In Case-II, wind farm provides the combined operation with PSP, where PSP operates at rated capacity of 76.06 MW during pumping mode by operating the pump at fixed speed as shown in Fig. 2.5 to 2.7. The pumped storage unit mostly operate in pumping mode to increase the energy level in the reservoir. During high market price, stored energy in pumped storage unit i.e. upper reservoir is utilized by operating hydraulic turbine to generate electricity for maximizing the total revenue and decreasing the market imbalances.

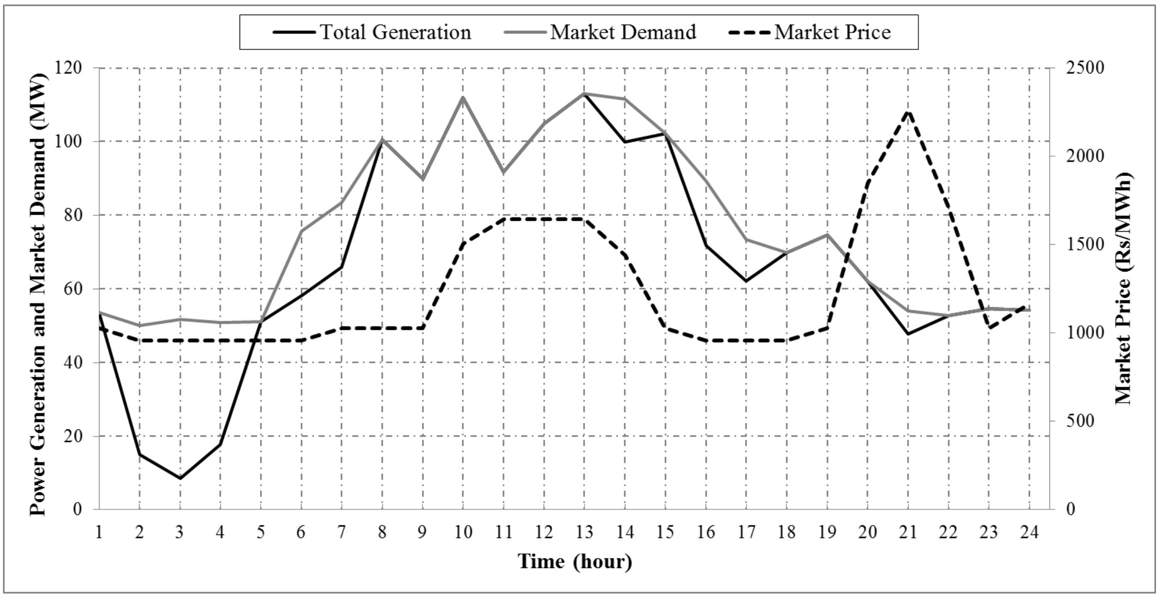


Fig. 2.5: Wind Farm and Pumped Storage Plant Operation (Case-II)

From Fig. 2.5 to 2.7, it is seen that during over generation of wind farm in hour 9 and during hours 19 to 21, the PSP tried to operate in pumping mode and stored the energy in the upper reservoir for the future use. During hours 10 to 17, it operated in generating mode using this stored energy. It is also clear that in the combined operation, PSP used the unutilized power of wind farm and reduced the market imbalance. Table 2.3 shows that overall profit is increased by 24% by operating the pump unit with wind farm in Case-II and the revenue loss is decreased by 59% as compared to Case-I.

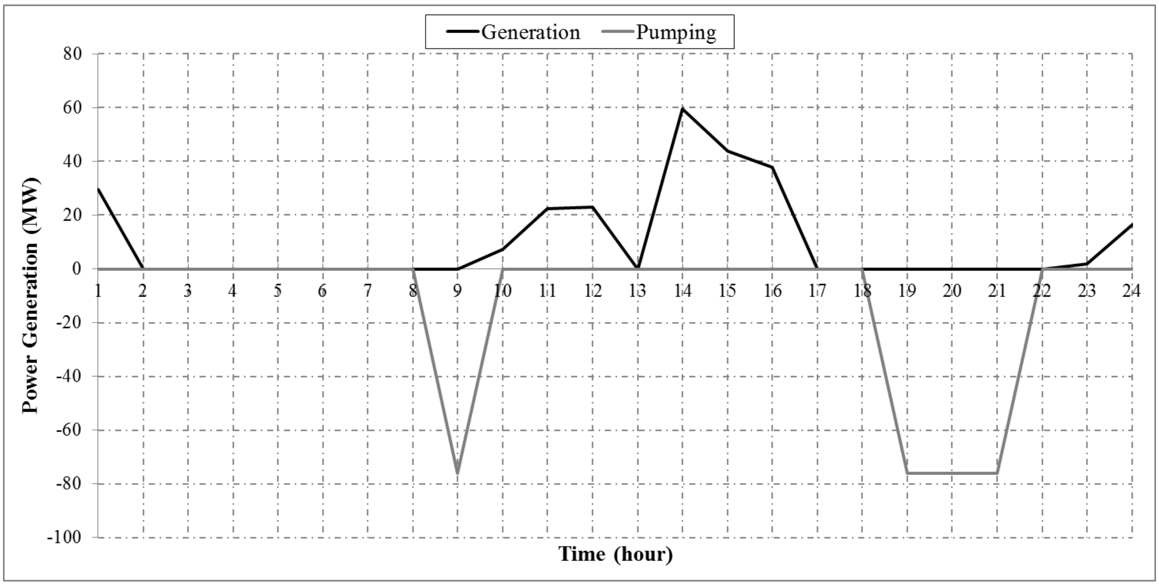


Fig. 2.6: Operation of Pumped Storage Plant (Case-II)

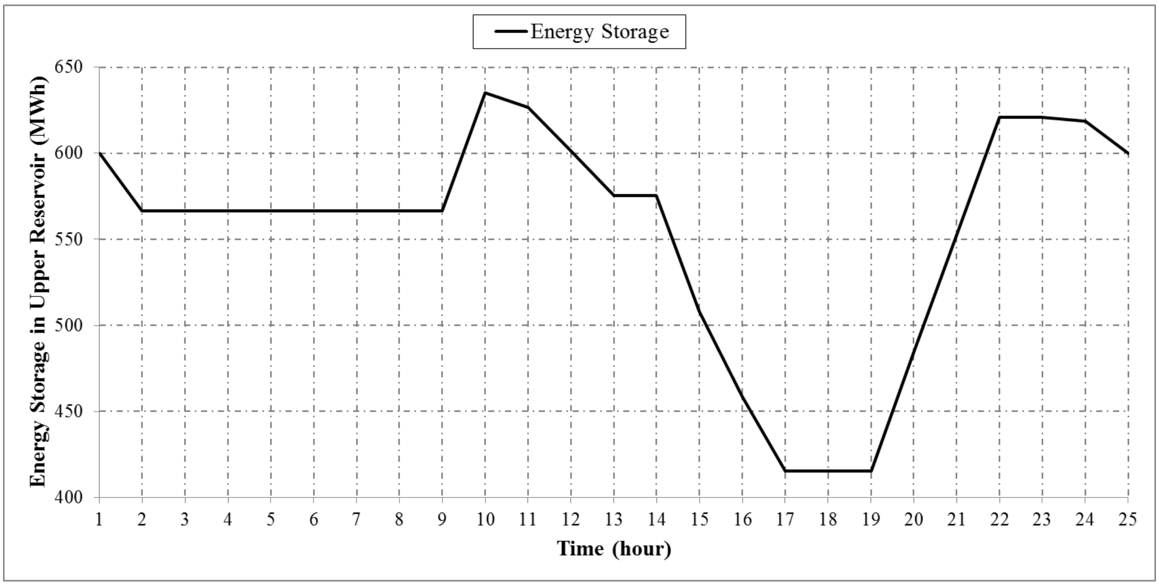


Fig. 2.7: Energy Storage Level in Upper Reservoir (Case-II)

In Case-III, pumping is done at two varying speeds with the help of converter-based controller, which allows the unit to operate at two different capacities to reduce the market imbalances. This variable operation operates the PSP at two capacities i.e 76.06 MW and 46.0 MW. This value is controlled by using two speed control variables. With the help of these controls, variable pumped storage unit operate efficiently during pumping mode thus increased the total revenue. Fig. 2.8 to 2.10, show that during hours 8 to 9, hours 4 to 6 and hours 19 to 22, the PSP tries to operate in pumping mode and store the energy in the upper reservoir. During the hours 10 to 17, it operates in generating mode and uses the stored energy from upper reservoir. Result presented in Table 2.3 shows that by operating the pump unit with the two speed mode, the overall profit increases by 28% as compared to Case-I and by 3% as compared to Case-II. It also decreased the revenue losses by 70% and 27% compared to Case-I and Case-II respectively.

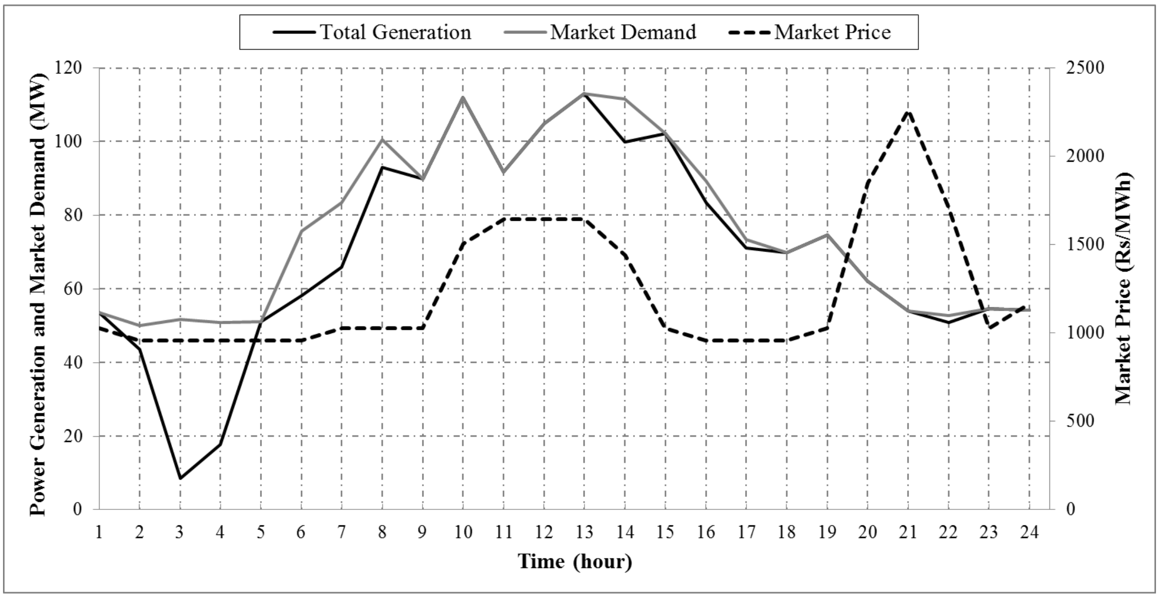


Fig. 2.8: Wind Farm and Pumped Storage Plant Operation (Case-III)

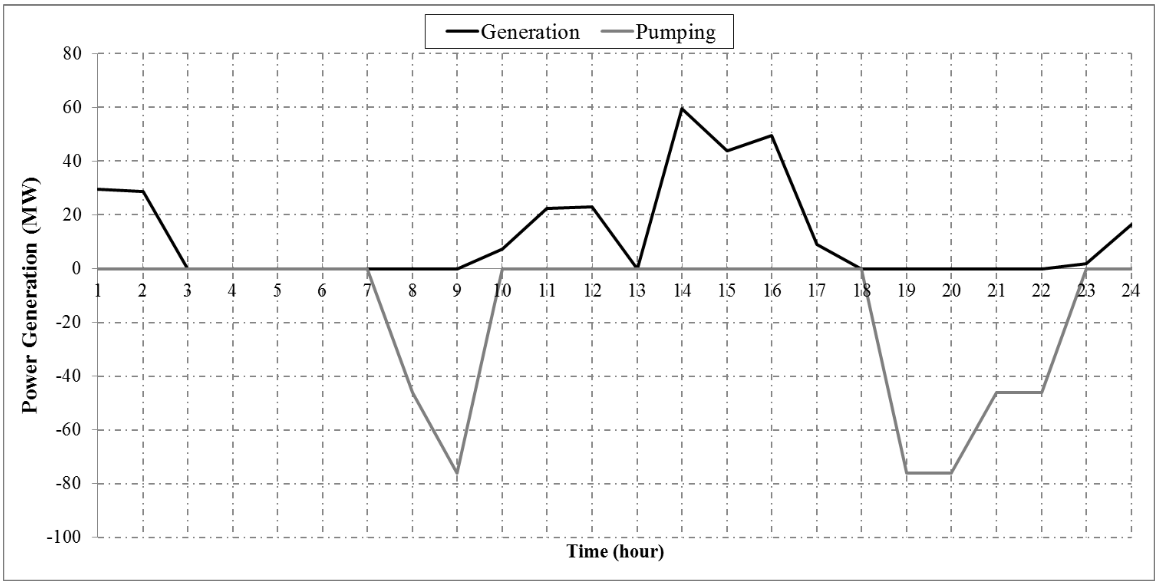


Fig. 2.9: Operation of Pumped Storage Plant (Case-III)

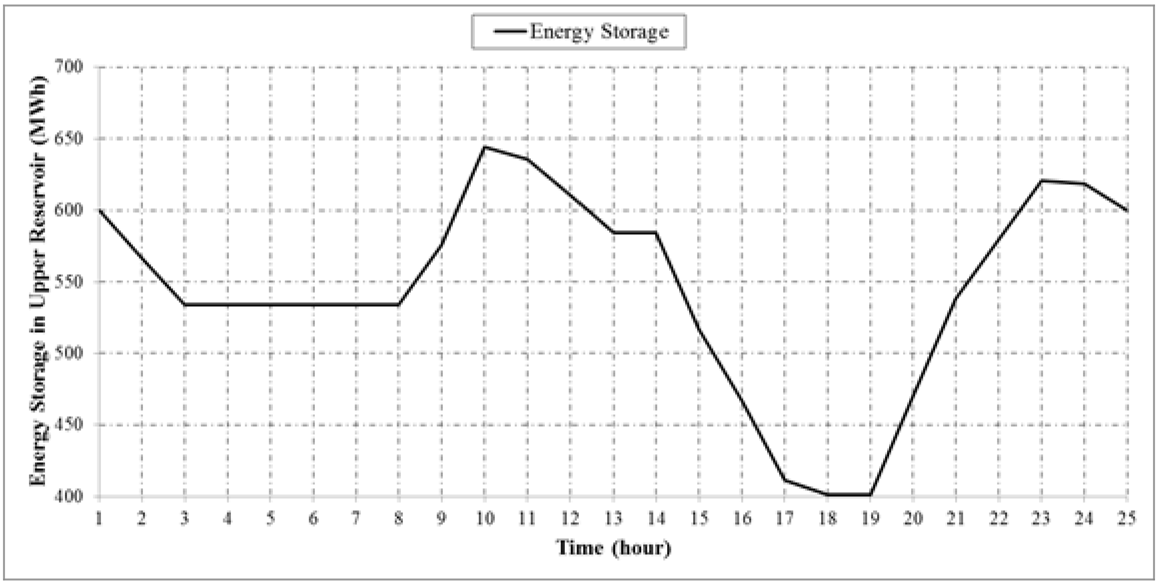


Fig. 2.10: Energy Storage Level in Upper Reservoir (Case-III)

In Case-IV, variable speed operation of PSP has been used. This variable operation operates the PSP between 76.06 MW and 46.0 MW. Fig. 2.11 to 2.13, show that revenue losses during hours 3 to 9 are reduced by variable operation of PSP compared to Case-III with only two speed PSP operation. Table 2.3 shows that by operating the pump unit in the variable speed mode as Case-IV, overall profit increased by *Rs.* 3030 and the revenue losses decreased by *Rs.* 910 as compared to Case-III.

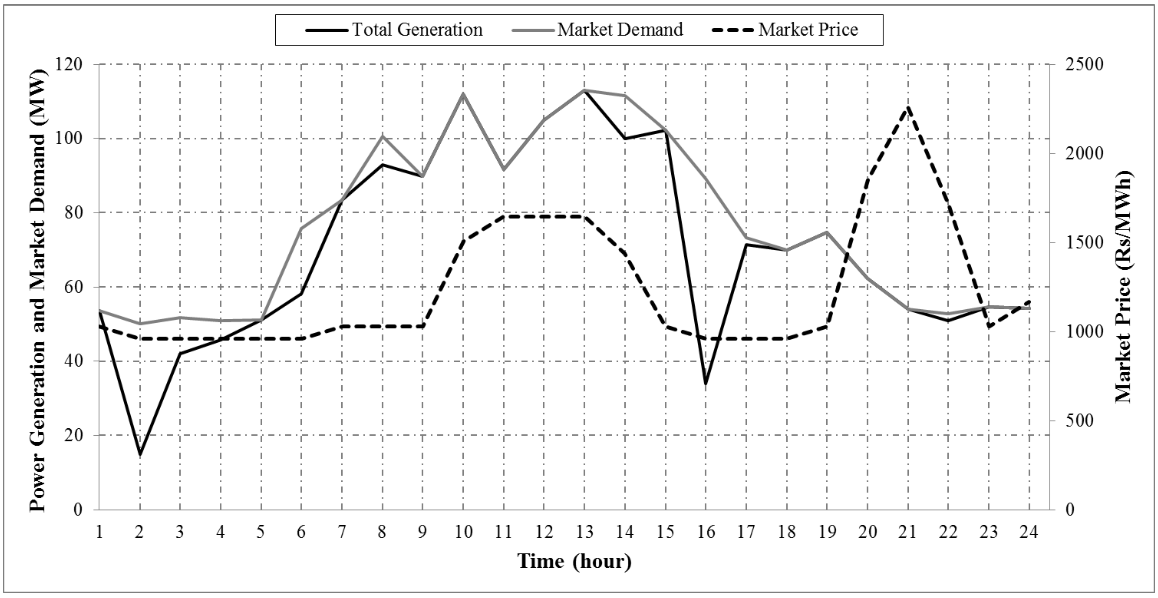


Fig. 2.11: Wind Farm and Pumped Storage Plant Operation (Case-IV)

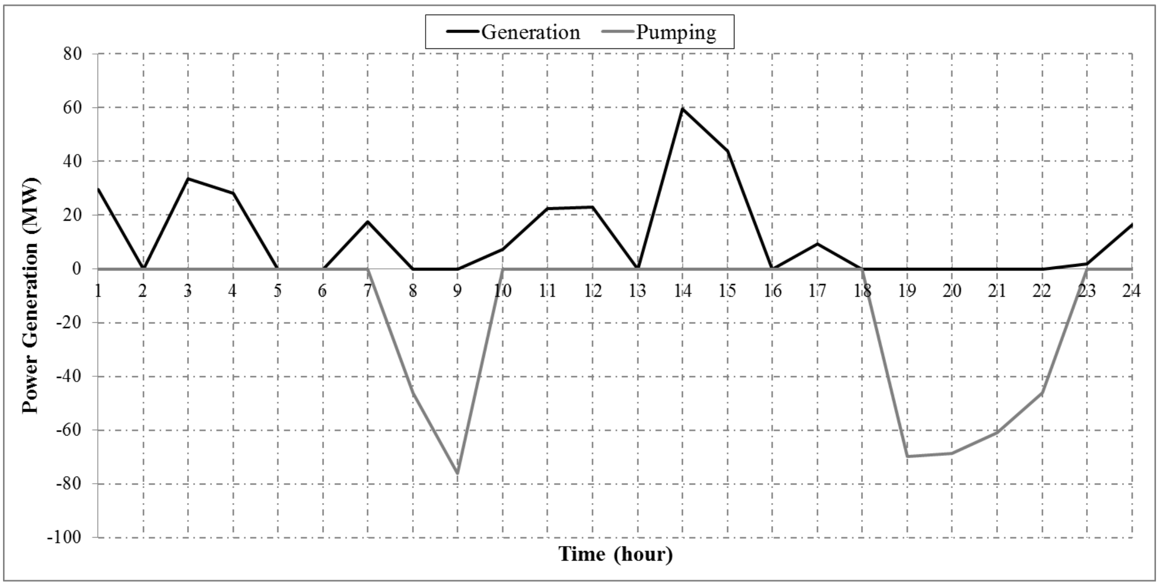


Fig. 2.12: Operation of Pumped Storage Plant (Case-IV)

Above results for all four cases in term of profit and revenue loss are compared and shown as Fig. 2.14. It can be concluded that the Case-IV is the best operation option compared to all the other three cases. The variable operation of PSP not only increased the overall profit across wind-PSP system but also reduced the revenue loss, which occur due to the difference between the generation and market demand. From the Table 2.3, it is also seen that the variable operation of PSP increases the operational reliability by providing more pumping and generation.

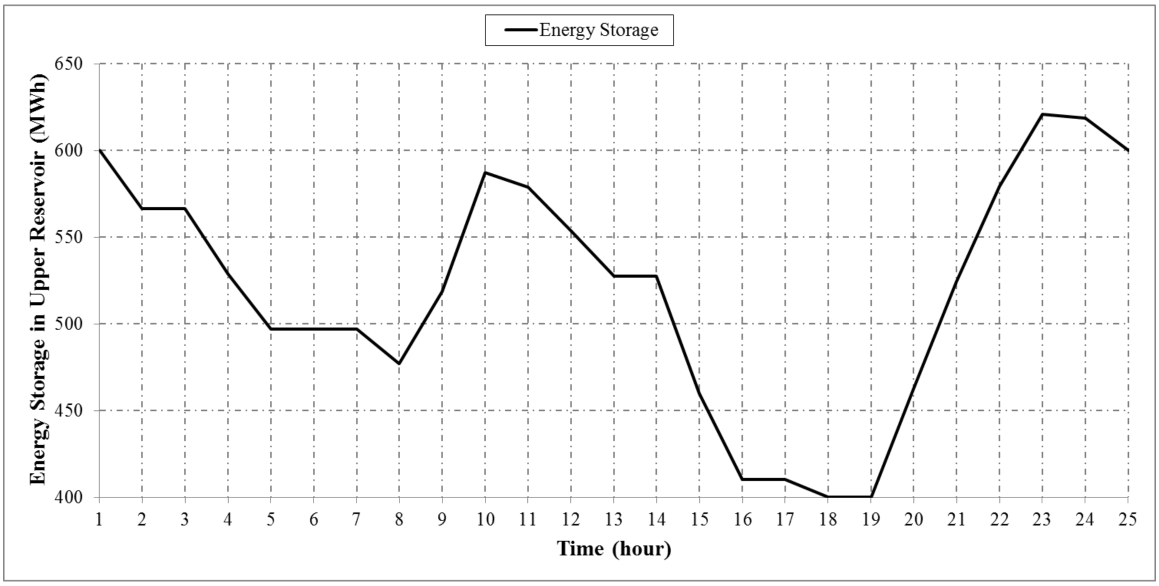


Fig. 2.13: Energy Storage Level in Upper Reservoir (Case-IV)

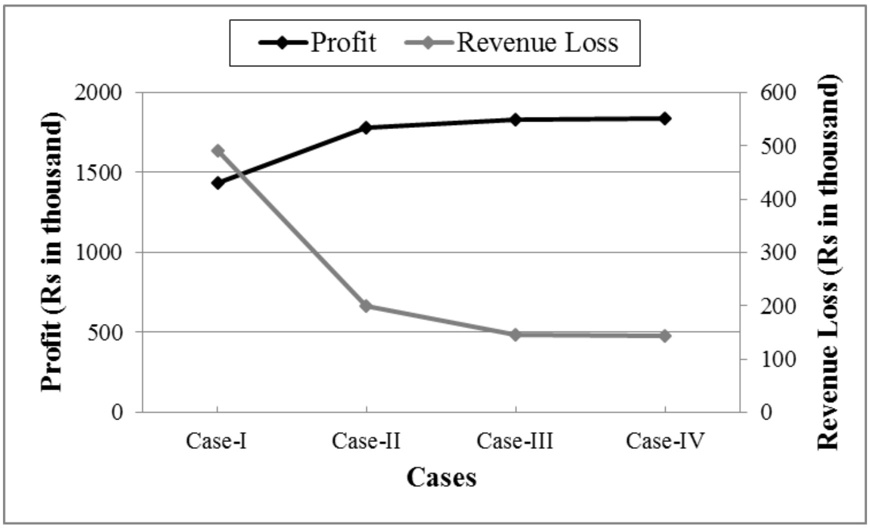


Fig. 2.14: Profit and revenue loss comparison

CHAPTER–3

WIND-PSP SCHEDULING CONSIDERING THE WIND UNCERTAINTY

3.1 INTRODUCTION

In the previous chapter, wind-PSP scheduling has been carried out without considering the effect of uncertainties. Uncertainties are always there in the electricity market affecting the scheduling operation of wind-PSP system. These uncertainties are present in the system in the form of price, demand and generation. For the power generation entities or the market operator, these uncertainties are mostly unknown at the time of scheduling or bidding. For example at the time of scheduling of wind generation, actual power available always remains unknown for market operator.

Most of scheduling problems are formulated as optimization problems. These optimization problems easily provide the optimal solution, if the input data are well defined and deterministic. In case input data are uncertain, the probability function is used to describe the data uncertainty. In case, the input data are represented by their corresponding expected values rather than probabilistic value then it may lead to a non-optimal solution. Alternatively, the probability distribution of input data can be represented by sets of scenarios and each set is combined with their probability of occurrence. For such instances, the sum of their probability of occurrence is always equal to one. Thus, by considering input data, the optimization problem can be implemented as a stochastic optimization problem.

During recent years, many researchers have used stochastic optimization problem to represent the market uncertainty. Garcia-Gonzalez et al. (2008) used two stage stochastic technique to make optimal decision under these uncertainties. The first-stage, decisions were for the hourly bids to be submitted to the day-ahead market and the second-stage decisions were related to the operation of the pumped-storage plant for each possible random variables i.e. wind and market price. Angarita et al. (2009) presented a stochastic approach to maximize the profit of wind-hydro system taking into account the uncertainty of wind power prediction. In this approach mixed-integer type problem was considered to decide the bidding strategy for pool-based electricity market.

For the present study, stochastic approach has been used to implement the wind-PSP scheduling problem considering the wind system uncertainty as input data. Under this problem, the average sum of each individual solution set of uncertain input data weighted by their associated probability is considered in order to achieve a single solution. A probability based forecasting model is used to forecast the uncertainty in the input data and probability distribution function has been computed for each set of input data. This solution has been found the best for all the individual solutions rather than solution from single set of input data. Three cases have been studied to check the optimality of the solution. In first two cases, wind-PSP system is considered to provide the scheduling under uncertain condition by operating the PSP in fixed and variable pumping mode, whereas in third case, the scheduling operation has been provided for grid connected wind-PSP to increase the overall profit under the deregulated environment.

3.2 WIND SPEED FORECASTING MODEL

To utilize the wind energy resource, it should be firstly analyzed and studied for its quantum, spatial and temporal distribution for the proper selection of wind turbine capacity. The analysis can also be done for the wind so that the electrical output is forecasted and utilized by day-ahead market. Therefore, it is important to study the characteristics of the wind frequency distribution. There are number of forecasting techniques available, which predict the electricity generation by wind turbines for the day ahead scheduling. Jie et al. (2011) used Hilbert-Huang Transform (HTT) and Artificial Neural Network (ANN) based forecasting techniques to predict the wind power on a set of selected wind farm. Presently, the Pearson model, the Rayleigh model and the Weibull model are usually applied to fit the distribution of wind speed frequency. In the wind farm, the Weibull distribution is often used to describe the characteristics of wind speed frequency (Al-Abbadi et al. 2009; Ruigang et al. 2011; Atawa 2011; Khathod et al 2010). In the present work, Weibull distribution is applied to fit the wind distribution in to six different scenarios. For this approach, whole 24 hours wind speed data has been divided in to 24 segments and each hourly segment is further divided into *n* discrete states (V_{min}, V_1, V_2…… V_{n-1}, V_{max}) using Eq. (3.1) and (3.2). Weibull distribution is a continuous function and different scenarios (S_1, S_2………S_{Ns-1}, S_{Ns}) have been developed using these discrete states as given in Eq. (3.4) and shown in Fig. 3.1. The probability density function (PDF) and cumulative distribution function (CDF) of 2- parameter Weibull distribution denoted as *f(x)* and *F(x)* respectively are given in Eq. (3.5) and (3.6).

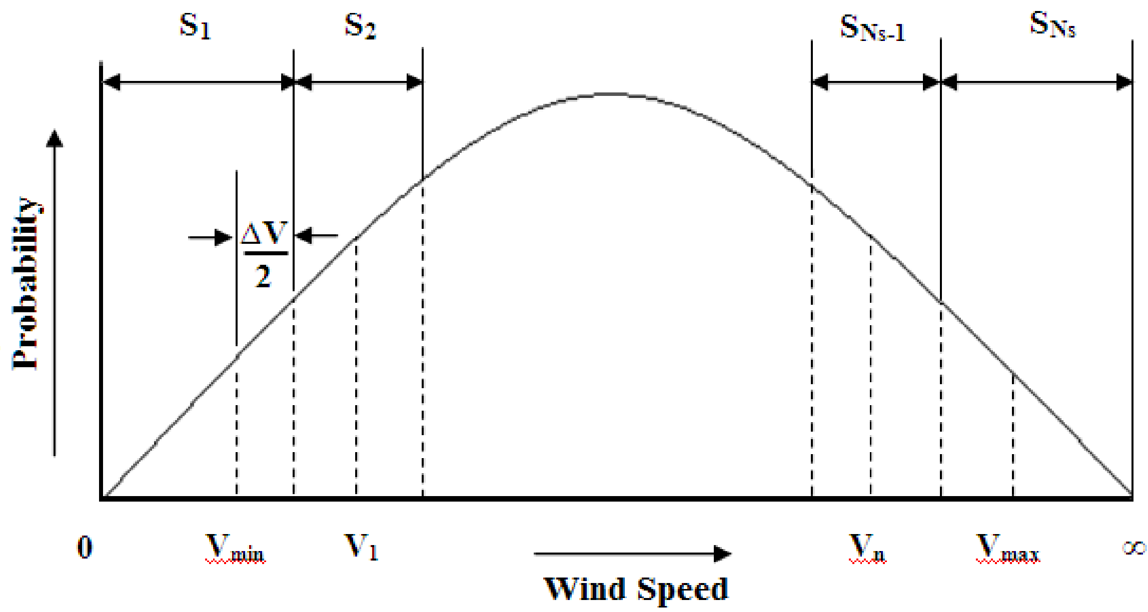


Fig. 3.1: Wind Speed probability distribution curve

$$V_1 = V_{\min} + \Delta V \tag{3.1}$$

$$V_i = V_{i-1} + \Delta V \quad \text{where } V_i = \{V_2, V_3 \ldots\ldots\ldots\ldots\ldots V_n\} \tag{3.2}$$

where

$$\Delta V = \frac{V_{\max} - V_{\min}}{n} \tag{3.3}$$

$$S_i = \begin{cases} 0 \rightarrow V_{\min} + \dfrac{\Delta V}{2} & for \quad i = 1 \\ V_i - \dfrac{\Delta V}{2} \rightarrow V_i + \dfrac{\Delta V}{2} & for \quad 1 < i < Ns \\ V_{\max} - \dfrac{\Delta V}{2} \rightarrow \infty & for \quad i = Ns \end{cases} \tag{3.4}$$

$$f(V) = ba^{-b} V^{b-1} e^{-\left(\frac{V}{a}\right)^b} \tag{3.5}$$

$$F(V) = \int_0^\infty ba^{-b} V^{b-1} e^{-\left(\frac{V}{a}\right)^b} dt \quad = 1 - e^{-\left(\frac{V}{a}\right)^b} \tag{3.6}$$

where, b is the form or shape parameter and a is the scale parameter indicating the main wind speed of the area. Parameters b and a can be obtained by the actual measurement of wind speed at the site as given in Table 3.1. V is the stochastic variable representing the uncertainty in the wind speed. PDF across these different scenarios have been calculated using Eq. (3.5) and (3.6). Similarly, for entire 24 segments, distribution function has been calculated using this approach to develop the wind forecasted model. This model has been used for forecasting the wind data for the day-ahead market by randomly generating the wind data across each scenario to flow a Weibull distribution as shown in Fig. 3.2.

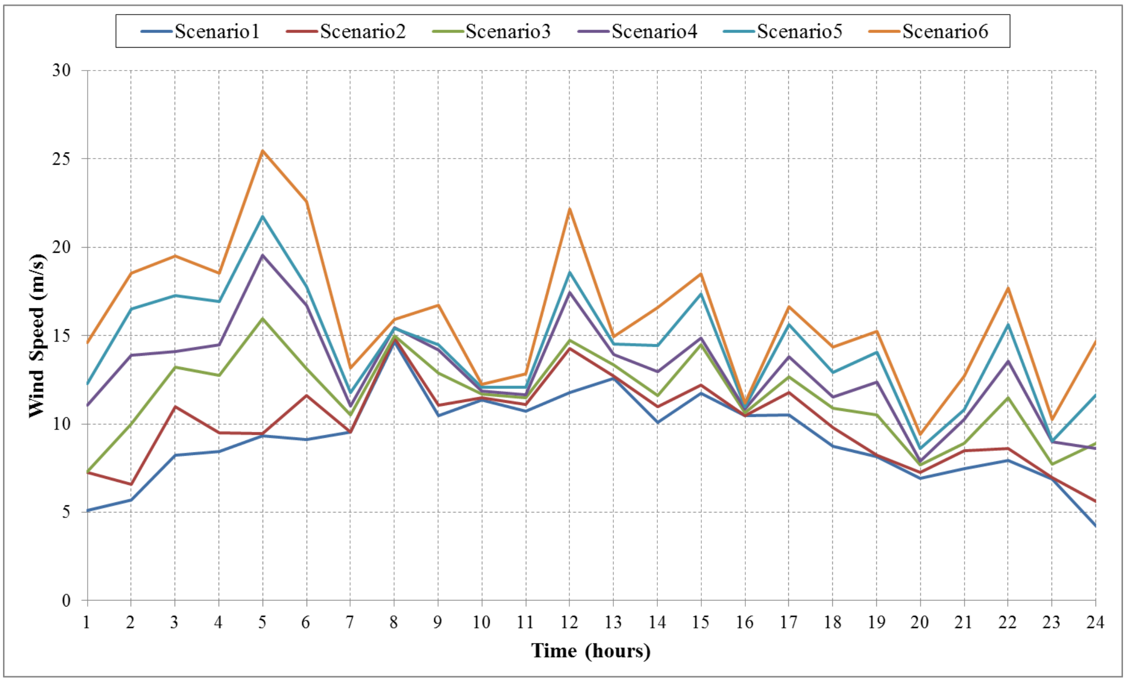


Fig. 3.2: Wind Speed for different scenarios

Table 3.1: Weibull distribution scale and shape parameters

Time (hours)	Weibull distribution parameters	
	Scale (a)	**Shape (b)**
1:00	12.00	2.30
2:00	12.45	2.45
3:00	12.43	2.34
4:00	11.89	2.51
5:00	12.49	2.77
6:00	12.89	2.51
7:00	13.13	2.65
8:00	12.61	2.50
9:00	12.97	2.88
10:00	13.15	3.57
11:00	12.45	3.44
12:00	12.05	3.28
13:00	12.92	2.44
14:00	12.26	2.18
15:00	11.69	2.29
16:00	12.05	2.28
17:00	12.00	2.02
18:00	12.16	2.04
19:00	11.74	2.20
20:00	12.80	2.14
21:00	12.49	2.64
22:00	12.35	2.61
23:00	12.46	2.47
24:00	12.36	2.86

Each randomly generated wind data is associated with a probability π as computed from the Eq. 3.7, where, *V(s)* represents the randomly generated wind data and *s* is the scenario index.

$$\pi(s) = f(s \mid V = V(s)) \qquad (3.7)$$

where $\sum_{s=S} \pi(s) = 1$

The probabilistic characteristic of the power generation from wind can be derived based on the wind speed and wind power. Currently, the most wind power generators in use are of variable speed, due to better feature of energy capture as compared to the fixed speed generators. The relationship between the input wind speed and power output can be approximately represented by Fig. 3.3. The power output corresponding to the regions given in Fig. 3.3 can be represented mathematically by Eq. (3.8).

$$Pw = \begin{cases} 0 & V \le V_{ci} & A \quad region \\ \phi(V) & V_{ci} < V \le V_r & B \quad region \\ P_r & V_r < V \le V_{co} & C \quad region \\ 0 & V > V_{co} & D \quad region \end{cases} \tag{3.8}$$

where, V_{ci} is the cut in wind speed, V_r is the wind speed at the rated power (P_r) and V_{co} is the cut out wind speed.

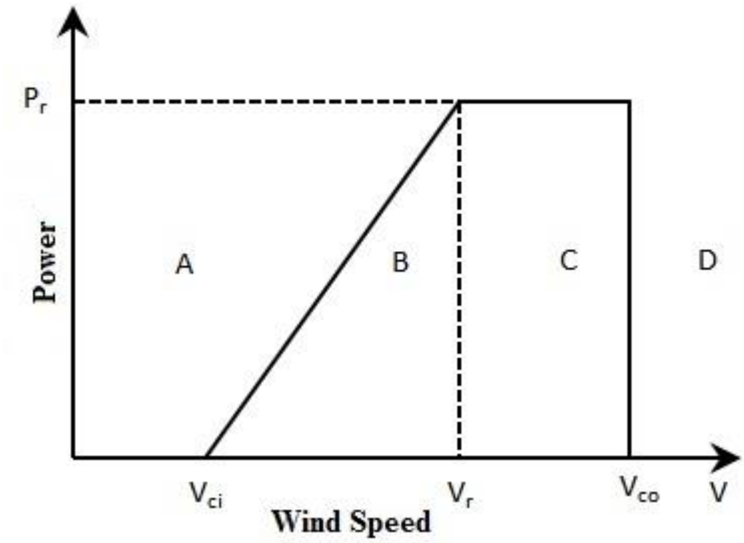


Fig. 3.3: Power Output Vs Wind Speed

3.3 WIND-PSP SCHEDULING CONSIDERING THE WIND UNCERTAINTY

In this study, PSP is used to provide hedging to a wind system to participate in the day-ahead market. In the PSP system, natural inflow in the upper reservoir is not considered, therefore it working is taken as offline mode. Water stored in upper reservoir is considered in the form of energy stored at the end of PSP operation during each period. Thus, the minimum and maximum capacity of upper reservoir will be expressed in the form of energy level. The initial and final energy levels of the upper reservoir are assumed to be equal whereas the effect of energy level in lower reservoir has been neglected.

The objective of this study is to analyse the benefit of the combined operation of wind–PSP system under deregulated market. A 24 hours time frame has been considered to provide the scheduling of wind and PSP under day-ahead market, where both wind and

PSP are operated as single entity and are not necessarily installed at the same or adjacent location. PSP consist of reversible turbine unit which can either generate electricity or pump the water as per requirement. Both the systems (wind and PSP) are connected to the grid as shown in Fig. 3.4. An optimal strategy is developed to efficiently utilize the power generated by wind and PSP as per the demand or bid received from the electricity market. Under this strategy, energy generated by the wind power plant is stored by pumping action during the low demand period. If wind power plant is unable to supply the power during the pumping mode, the required power for pumping is drawn from the grid. Variable speed unit was used during the pumping mode for utilizing the wind power variation effectively. Wind energy has been forecasted for day-ahead market using Weibull distribution technique as given in section 3.2. The imbalance in forecasted data and market demand has been reduced by controlling the variable speed of PSP in both generating and pumping mode. The various cases considered in the study are described below:

Case-I: Single unit PSP has been considered to provide combined operation with the wind system. The unit of PSP operates as conventional PSP unit in pumping mode at fixed speed and operates as conventional hydro generating unit during generating mode.

Case-II: Adjustable speed pumped storage unit has been considered to provide the variable pumping operation. Both generation and pumping operations have been carried out between their given minimum and maximum speed limits.

Case-III: In this case, combined operation of wind-PSP system has been further improved by operating under grid connected day-ahead market. A variable speed pumped storage unit has been considered to increase the overall profit across the system.

3.3.1 Objective Function

In the market based system, revenue or profit of the PSP is maximized by operating in generation mode when market price is high and in pumping mode when the price is low. The income of a PSP includes net revenue received by selling energy in the day-ahead market when it is operating in the generating mode and buying energy while operating in pumping mode. The objective function for this problem has been formulated to maximize the total revenue obtained from the combined operation of pump storage and wind power plant as given in Eq. (3.8).

$$Maximize: \quad \sum_{s=1}^{Ns} \sum_{t=1}^{T} \pi(t,s)\left(R_{psp}(t,s) + R_{wind}(t,s) - R_{loss}(t,s)\right) \tag{3.8}$$

This objective function consists of the revenue of pump storage plant $R_{psp}(t,s)$, revenue of wind farm $R_{wind}(t,s)$. $\pi(t,s)$ is the probability associated with the s^{th} scenario at t^{th} hour. T is the total time period and Ns is the total number of scenarios. The total revenue of PSP, $R_{psp}(t,s)$ is given in Eq. (3.9).

$$R_{psp}(t,s) = R_{gen}(t,s) - R_{pump}(t,s) \tag{3.9}$$

where, $R_{gen}(t,s)$ is the revenue of the PSP in generating mode and $R_{pump}(t,s)$ is the revenue of PSP during pumping mode.

$R_{gen}(t,s)$ is defined as the product of the power generated by PSP ($P_{gen}(t,s)$) during the generating mode at the market price ($\lambda_{mkt}(t,s)$), where $s(t,s)$ is the switching variable for generating mode as given in Eq. (3.10).

$$R_{gen}(t,s) = s(t,s) \times P_{gen}(t,s) \times \lambda_{mkt}(t,s) \tag{3.10}$$

During the pumping, the PSP uses the power from two sources i.e. one from the wind power plant and other from the grid. The total revenue during the pumping mode is the sum of revenue from the wind power plant generation as well as from the grid as given in Eq. (3.11).

$$R_{pump}(t,s) = Pw_{pump}(t,s) \times \lambda_{wind} + Pg_{pump}(t,s) \times \lambda_{mkt}(t,s) \tag{3.11}$$

where, λ_{wind} is the price paid by the PSP to the market for utilizing the wind power for pumping operation. This remains constant for whole period.

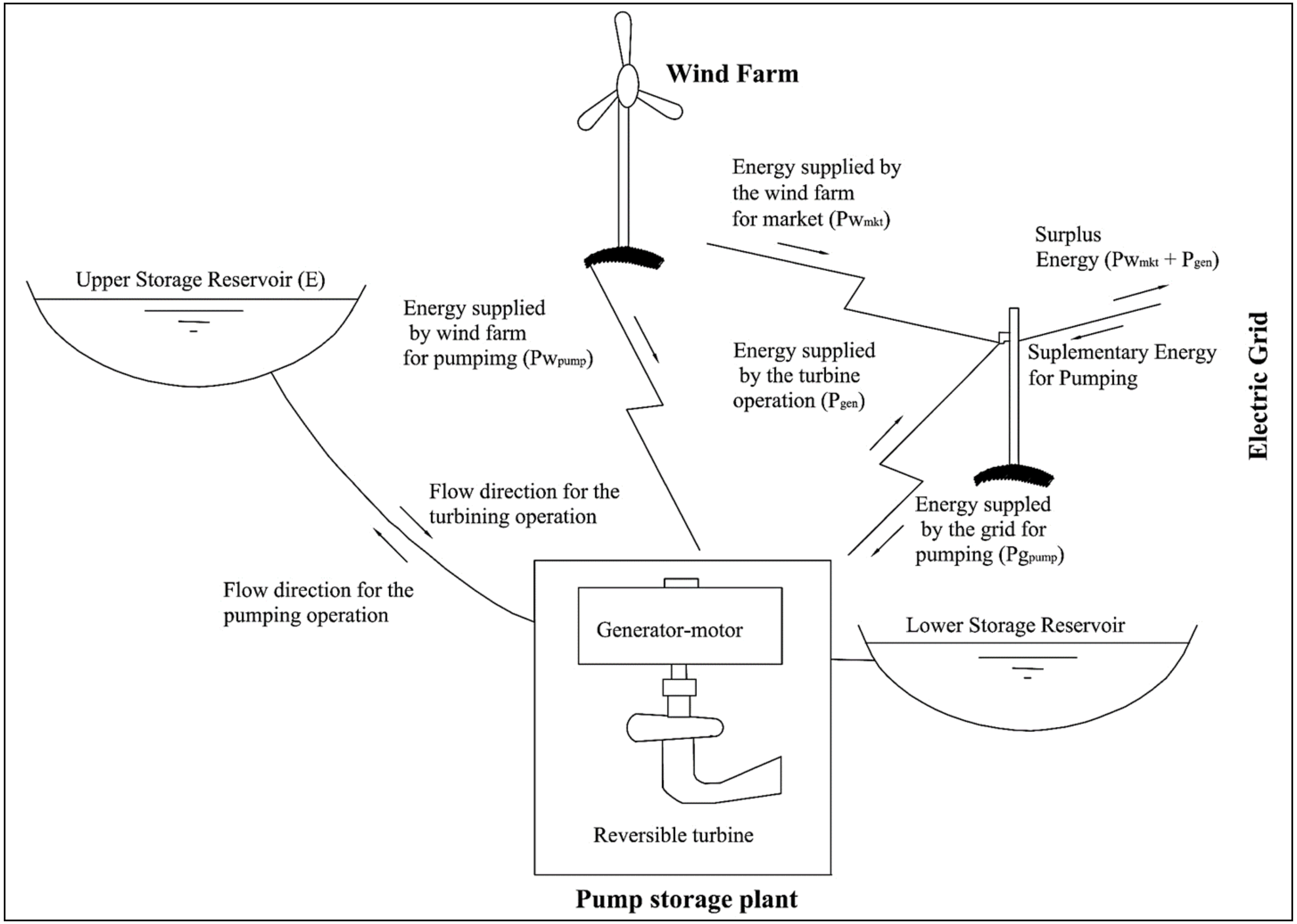


Fig. 3.4: Wind-pumped storage plant model

$R_{wind}(t,s)$ in Eq. (3.12), is the revenue from the power supplied by wind power plant to the market, referred as $Pw_{mkt}(t,s)$.

$$R_{wind}(t,s) = Pw_{mkt}(t,s) \times \lambda_{mkt}(t,s) \qquad (3.12)$$

Eq. (3.13) defines the expected revenue loss $R_{loss}(t,s)$ due to the market imbalances.

$$R_{loss}(t,s) = \omega \times \lambda_{mkt}(t) \times [P_d(t) - Pw_{mkt}(t,s) - s(t,s) \times P_{gen}(t,s)] \qquad (3.13)$$

where, ω is the penalty imposed by the market for creating imbalance between generation and demand.

3.3.2 Control Variables

A control variable $s(t,s)$ used in the problem formulation controls the operation of PSP in generating mode as given in Eq. 3.14, whereas, $s_p(t,s)$ is the variable which controls the operation of PSP in pumping mode as given in Eq. (3.15).

$$s(t,s) \in \{0,1\} \qquad (3.14)$$

$$s_p(t,s) \in \{0,1\} \qquad (3.15)$$

3.3.3 Constraints

Above objective function has been formulated subjected to the following equality and inequality constraints:

3.3.3.1 Grid Pumping Limits

In this approach, wind-pumped storage system is connected with the grid to supply the pumping power to the pumped storage plant. The power supplied by the grid for pumping has upper and lower limit given in Eq. (3.16).

$$Pg_{pump}^{min} \le Pg_{pump}(t,s) \le Pg_{pump}^{max} \qquad (3.16)$$

3.3.3.2 Wind Power Constraint

The total power generated by the wind power plant is $Pw_{gen}(t,s)$. During the operation, it is possible that it not utilized all the power generated by the wind power plant. The unutilized power is determined by the constraint given in Eq. (3.17), where $Pw_{pump}(t,s)$ is the power consumed by the PSP during pumping and $Pw_{mkt}(t,s)$ is the power consumed by the market demand and $Pw_{unutilized}(t,s)$ is the unutilized power and can be determined as per Eq. (3.17).

$$Pw_{unutilized}(t,s) = Pw_{gen}(t,s) - Pw_{pump}(t,s) - Pw_{mkt}(t,s) \tag{3.17}$$

3.3.3.3 Pumping Constraint

For the pumping operation, the PSP can either take power from the grid or wind power plant as given in the Eq. (3.18).

$$P_p(t,s) \times s_p(t,s) = Pw_{pump}(t,s) + Pg_{pump}(t,s) \tag{3.18}$$

where, $Pw_{pump}(t,s)$ is the power consumed by the PSP from the wind power plant and $Pg_{pump}(t,s)$ is the power consumed by the PSP form the grid. $P_p(t,s)$ is the total power consumed at t^{th} time of s^{th} scenario during pumping mode and $sp(t,s)$ is the switching variable for pumping mode.

3.3.3.4 Imbalance Constraints

$R_{loss}(t,s)$ given in Eq. (3.19), represents the total imbalance in the market, which implied that the total generation provided by the market is always equal or less than the total demand across the market to avoid the over generation of power due to market restriction.

$$R_{loss}(t,s) \geq 0 \tag{3.19}$$

3.3.3.5 Energy Balance Constraint

The Eq. (3.20) determines the energy balance in the upper reservoir. At the beginning of $(t+1)^{th}$ hour, the energy in the upper reservoir $E(t+1,s)$ is the sum of initial energy level in the reservoir $E(t,s)$ at t^{th} hour, $P_p(t,s)\times[1-s(t,s)]\times\eta_p$ as the energy supplied to the upper reservoir during pumping and $P_{gen}(t,s)\times s(t,s)/\eta_h$ is the energy released from the upper reservoir during generation mode, whereas $s(t,s)$ and $s_p(t,s)$ are the mode control variables. Δt is the time deviation or the time interval between each period, η_p and η_h are the efficiencies of pumped storage plant during pumping and generating modes respectively.

$$E(t+1,s) = (P_p(t,s)\times s_p(t,s)\times\eta_p - P_{gen}(t,s)\times s(t,s)/\eta_h)\times\Delta t + E(t,s) \tag{3.20}$$

3.3.3.6 Reservoir Limit

The energy stored in the upper reservoir has upper and lower limit as given in Eq. (3.21).

$$E^{\max} \le E(t,s) \le E^{\min} \tag{3.21}$$

where, E^{max} and E^{min} are the minimum and maximum energy level in the upper reservoir.

3.3.3.7 Generation Limit

This constraint keeps the power generated by the PSP within the upper and lower limit as given in Eq. (3.22).

$$P_{gen}^{\min} \le P_{gen}(t,s) \le P_{gen}^{\max} \tag{3.22}$$

where, $P_{gen}^{\min}$ and $P_{gen}^{\max}$ are the minimum and maximum power generation limits of PSP.

3.3.3.8 Pumping Limit

This constraint keeps the power consumed by the pumped storage plant within the upper and lower limit and given in Eq. (3.23).

$$P_p^{\min} \leq P_p(t,s) \leq P_p^{\max} \tag{3.23}$$

where, $P_p^{\min}$ and $P_p^{\max}$ are the minimum and maximum pumping limits of PSP.

3.3.3.9 Switching Constraint

This constraint controls the operation of PSP between the generating and pumping mode and does not allow both operations at the same time as given in Eq. (3.24).

$$s(t,s) \times s_p(t,s) = 0 \tag{3.24}$$

where, $s(t,s)$ and $s_p(t,s)$ are the control variables of PSP during generating and pumping modes respectively.

3.4 METHODOLOGY

In this chapter, stochastic mixed integer type problem is formulated in the AMPL software to optimize the solution under uncertainty. Uncertainty across the wind-PSP system has been determined by forecasting the wind data in the form of different scenarios. Here, each scenario revealed a random variable, which represents the uncertainty in wind data. Each random variable provided with their individual probability and is described in section 3.2. To optimize the operation of wind-PSP system, scheduling across each random variable has been determined with the help of KINTRO solver. Each random variable provided an individual solution. In order to obtain a single solution, average sum of each individual solution has been determined, where each solution was weighted by their associated probability.

3.5 RESULTS AND DISCUSSIONS

For this stochastic mixed integer problem, 150 MW wind farm data has been taken from Alta wind energy center (Alta-I), located at California, USA consisting of 100 units of 1.5 MW wind turbines each. The wind data were considered in the form of stochastic variable to determine the wind uncertainty. This stochastic wind data have been divided into six different scenarios. In the optimization process, the wind power output across each scenario remains fixed at its forecasted value. Stochastic approach has been applied to introduce the effect of wind data uncertainty and the solution is optimized to increase the overall profit by satisfying the market demand. A penalty factor (ω) has also been introduced for any unsatisfied market demand and considered equal to 0.75. Three cases have been analyzed to prove the optimality of the solution. In all the cases, reversible type turbine was used which operates both in pumping as well as generating mode. In Case-I, the pumped storage unit operates at its rated power during pumping mode, where as in the Case-II and III, pumping input power varies by variable speed type unit. The rating of both PSP units has been taken from Hiwasse Dam unit-2 (Hiwasse Dam unit-2, 1956) as mentioned in Table 3.2. For both the cases, the initial and final levels of the upper reservoir are considered equal, so that, it can be utilized for next day scheduling as given in Table 3.2.

Both wind and PSP supply the power to the market at the given market price. PSP is connected with the grid so that, it can draw the power from the grid for pumping at the market price, whereas, pumping by using wind power is at constant price (*Rs* 548 per MWh). Grid based pumping energy cannot be more than 300 MWh with the maximum power capacity limit of 100 MW as shown in Table 3.2. Table 3.3 and 3.4 represent the market imbalances and the wind energy utilization across each scenario respectively. In third case, grid connected wind-PSP system has been considered and the amount of grid power utilized in this case has been given in Table 3.5.

Table 3.2: Wind PSP System

Data for Wind Farm				
Number of units	**Cut in wind speed (*m/s*)**	**Cut out wind speed (*m/s*)**	**Rated Wind Speed(*m/s*)**	**Rated Power (*kW* per unit)**
100	3	26	15	1500
Data For PSP unit				
Mode of Operation	**Efficiency %**	**Maximum (in MW)**	**Minimum (in MW)**	
Generation	84.4	59.65	0	
Pumping	90.0	76.06	46.00	
Data for upper reservoir (MWh)				
Reservoir Type	**Maximum**	**Minimum**	**Initial**	**Final**
Offline	1200	400	600	600
Data for Power Supplied by Grid for Pumping				
Maximum (MW)	**Minimum (MW)**	**Total (MWh)**		
100	0	300		

Table 3.3: Market imbalances across each scenario

Scenarios	**Total Market Imbalances (MWh)**		
	Case-I	**Case-II**	**Case-III**
1	686.02	658.88	417.12
2	136.34	95.88	28.65
3	0.76	0.76	0.76
4	3.69	3.69	3.69
5	0	0	0
6	0	0	0
Total	826.81	759.22	450.22

Table 3.4: Wind energy utilized by each scenario

Scenarios	**Wind Utilization in Revenue (MWh)**		
	Case-I	**Case-II**	**Case-III**
1	1995.05	2057.33	2142.91
2	2363.19	2414.59	2422.94
3	2680.30	2703.45	2703.45
4	2858.91	2858.91	2858.91
5	2862.61	2883.14	2883.14
6	2862.61	2886.52	2886.52
Total	15622.67	15803.95	15897.88

Table 3.5: Total grid pumping by each scenario in Case-III

Scenarios	Total Grid Pumping (MWh)
1	300.0
2	73.0
3	0.0
4	0.0
5	0.0
6	0.0

In the first case, wind farm provided the combined operation with PSP, where PSP operates at rated capacity of 76.06 MW during pumping mode at fixed speed as shown in Fig. 3.5 to 3.7. In this system, wind data is presented in the form of scenario to represents the wind uncertainty. Combined operation of wind-PSP system for each scenario has been presented as the Fig. 3.5 and 3.6. From the Table 3.3, it is seen that under 1st, 2nd and 3rd scenarios, the power generated by wind-PSP system is low, so that imbalance cost during these scenarios are very high as compared to the other scenarios. In these scenarios, maximum number of pumping operations have been provided to utilize the stored energy between 19th and 22nd hours, when the market price was high. In the other scenarios, wind power was mostly sufficient to supply the market demand and provided less pumping operation to increase the overall revenue. From the Table 3.6, it is seen that the overall profit of wind-PSP system is *Rs.* 2960.627 thousand and the market imbalance is nearly 826.81 MWh.

Table 3.6: Total expected profit and market imbalance for all cases

Cases	Total Expected Profit (thousand Rs)	Market Imbalance (MWh)
Case-I	2960.63	826.81
Case-II	2997.00	759.22
Case-III	3121.82	450.22

From the above analysis, it has been found that PSP units were scheduled to generate power especially in periods of high market price, thus increasing the revenue. It is also seen that this type of scheduling has reduced the imbalance between the generation and demand, thus avoiding the penalty during high market price.

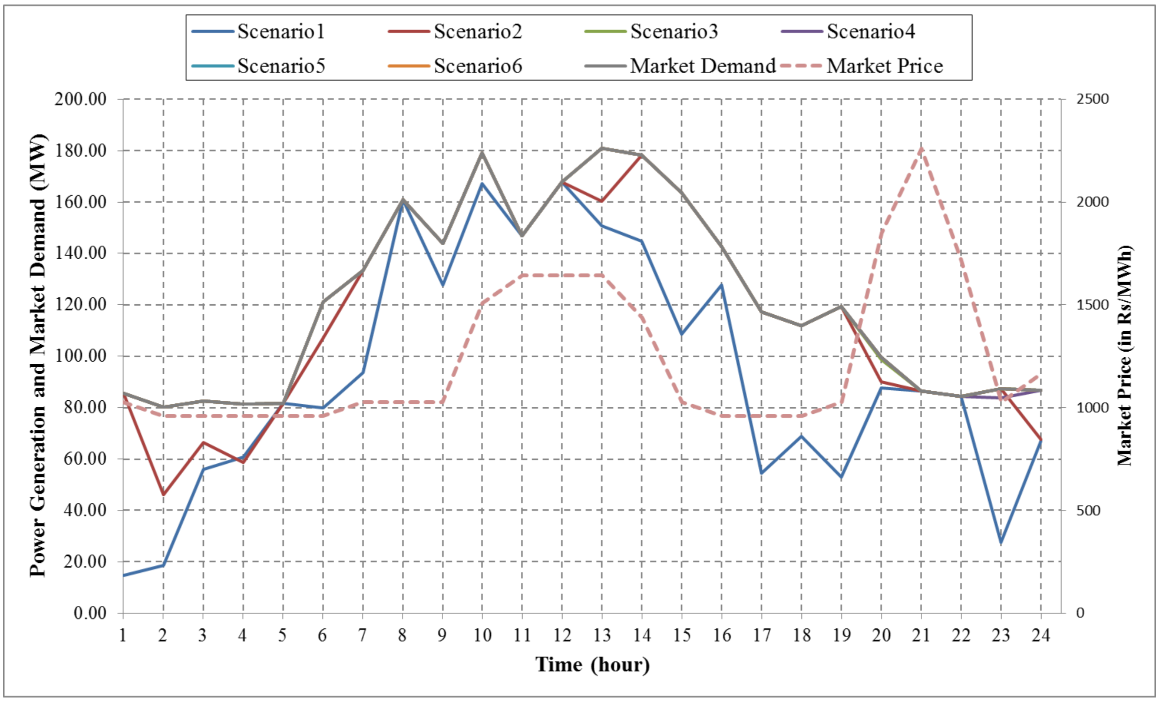


Fig. 3.5 Wind Farm and Pumped Storage Plant Operation (Case-I)

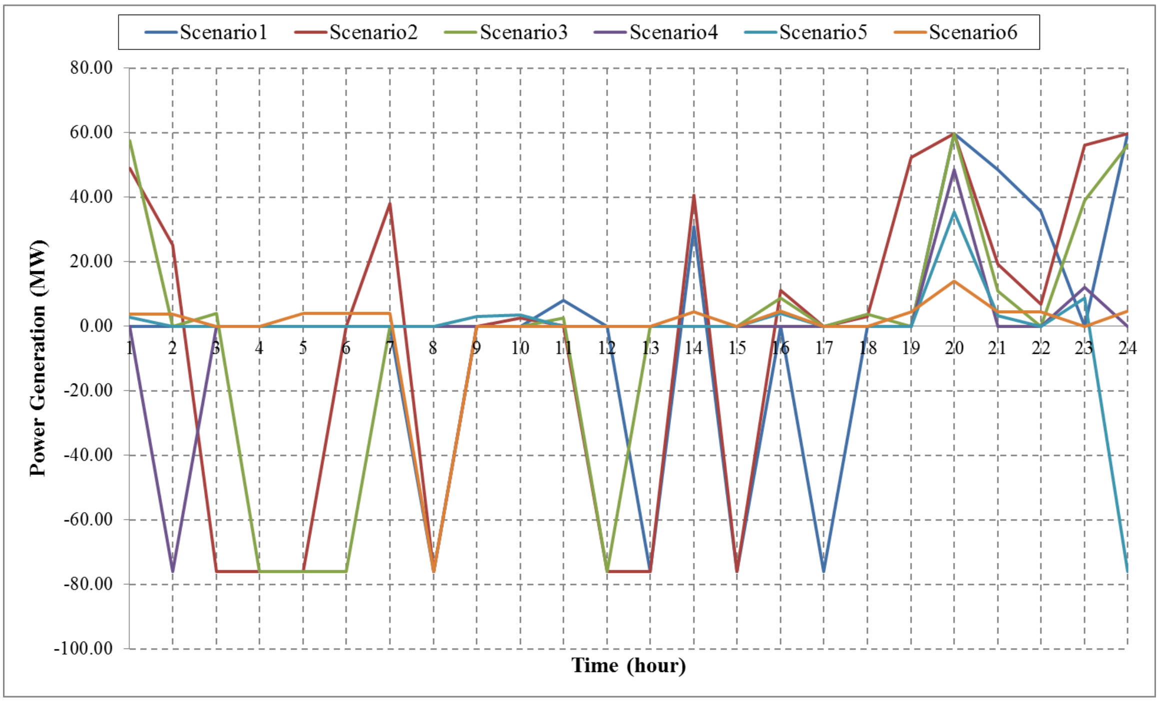


Fig. 3.6: Operation of Pumped Storage Plant (Case-I)

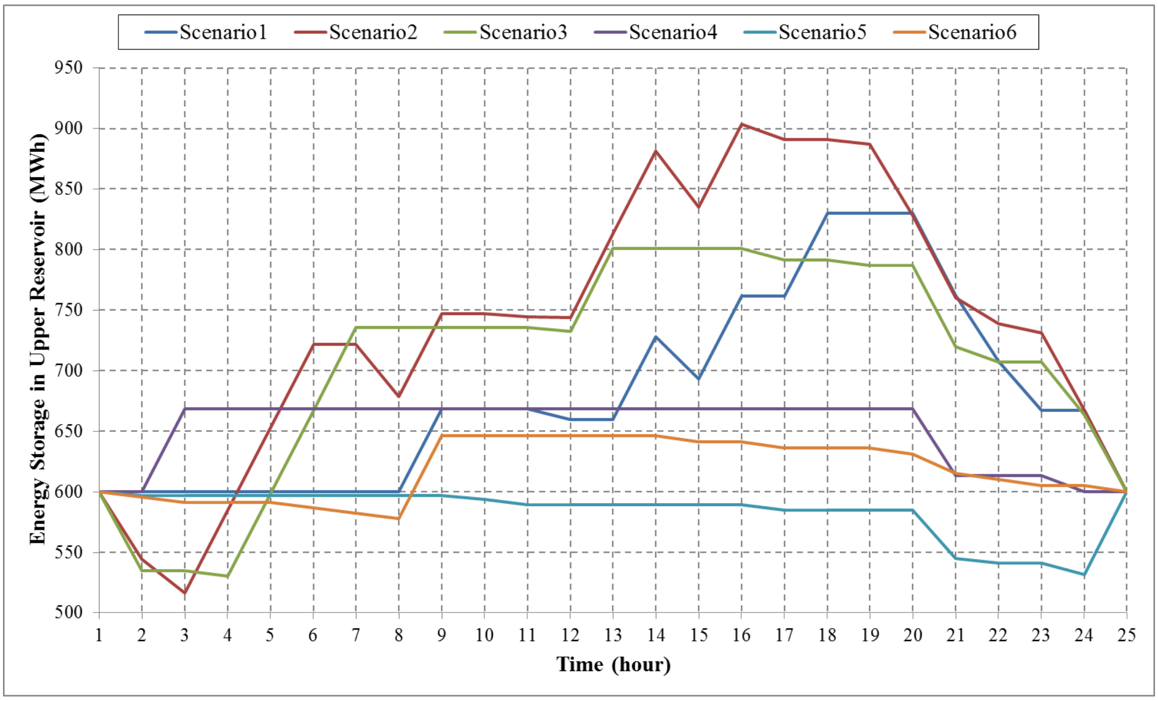


Fig. 3.7: Energy Storage Level in Upper Reservoir (Case-I)

In second case, multi speed operation of PSP has been provided. The PSP operated between 76.06 MW and 46.0 MW during this variable operation. Fig. 3.8 to 3.10, show that the variable operation increased the pumping by 20% during 1st, 2nd and 3rd scenarios and by 35% during 5th and 6th scenarios, thereby improved the revenue across Wind-PSP system. Table 3.6 shows that by operating the pump unit in the variable speed mode (Case-II), the overall profit is increased by 1.2 % and the market imbalance reduced by 8% as compared to Case-I. Also the total wind utilization improved in the market by 1%.

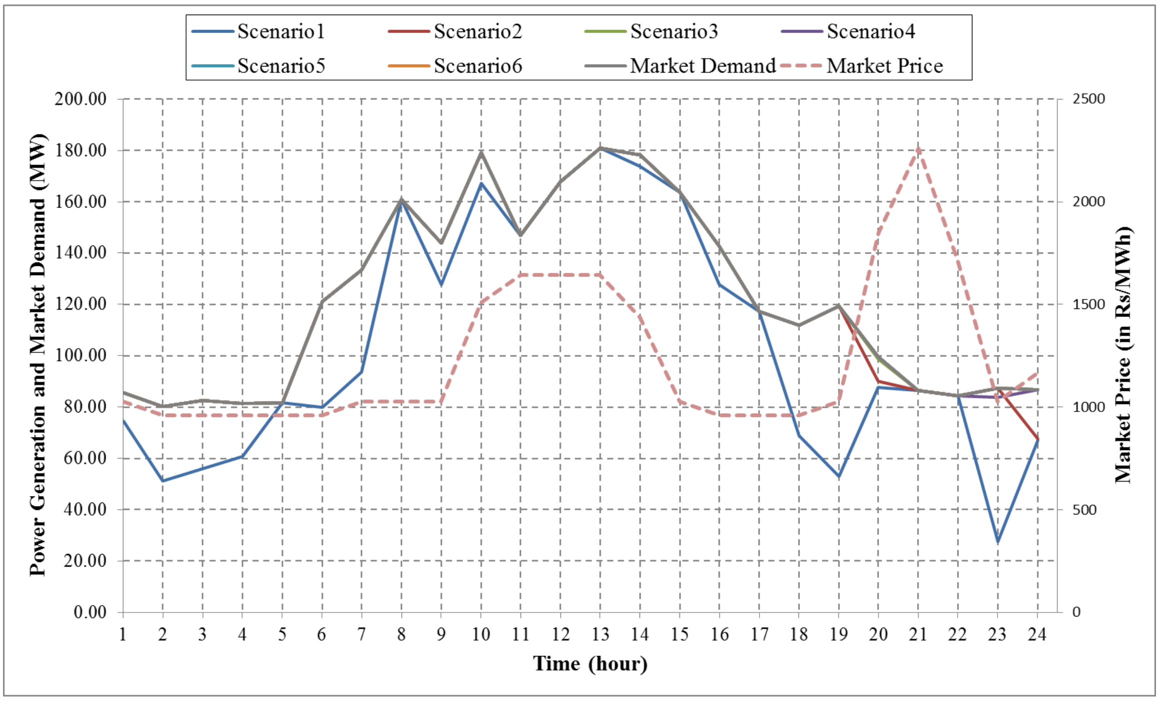


Fig. 3.8: Wind Farm and Pumped Storage Plant Operation (Case-II)

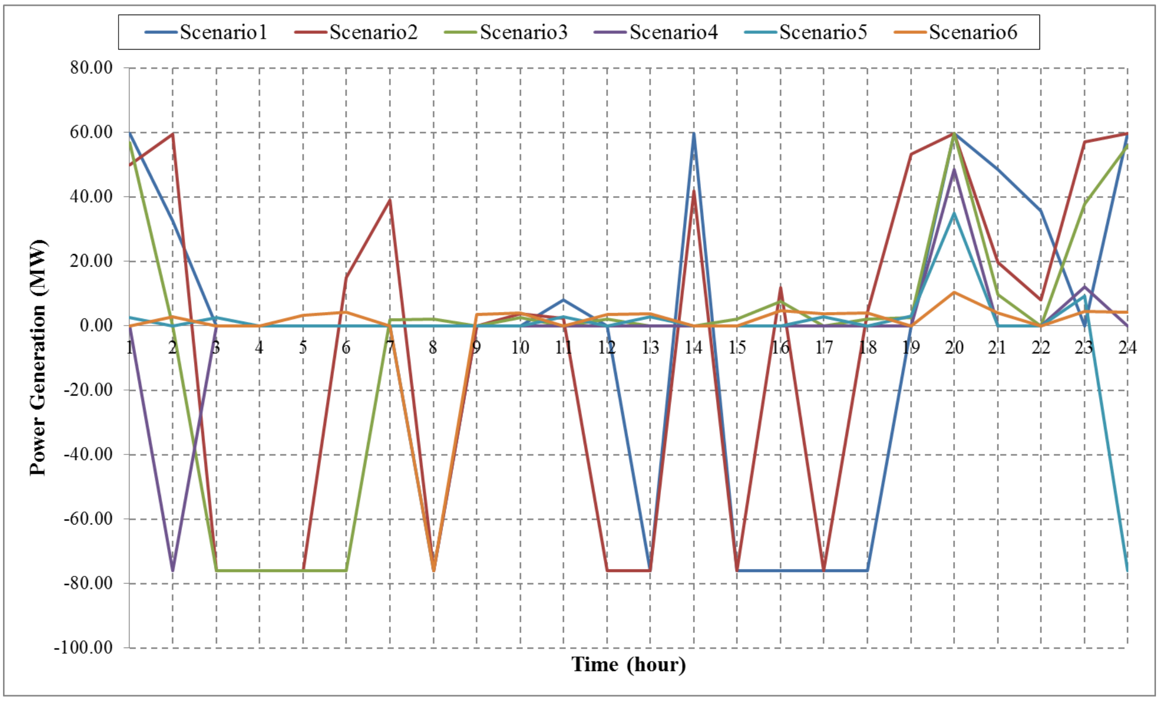


Fig. 3.9: Operation of Pumped Storage Plant (Case-II)

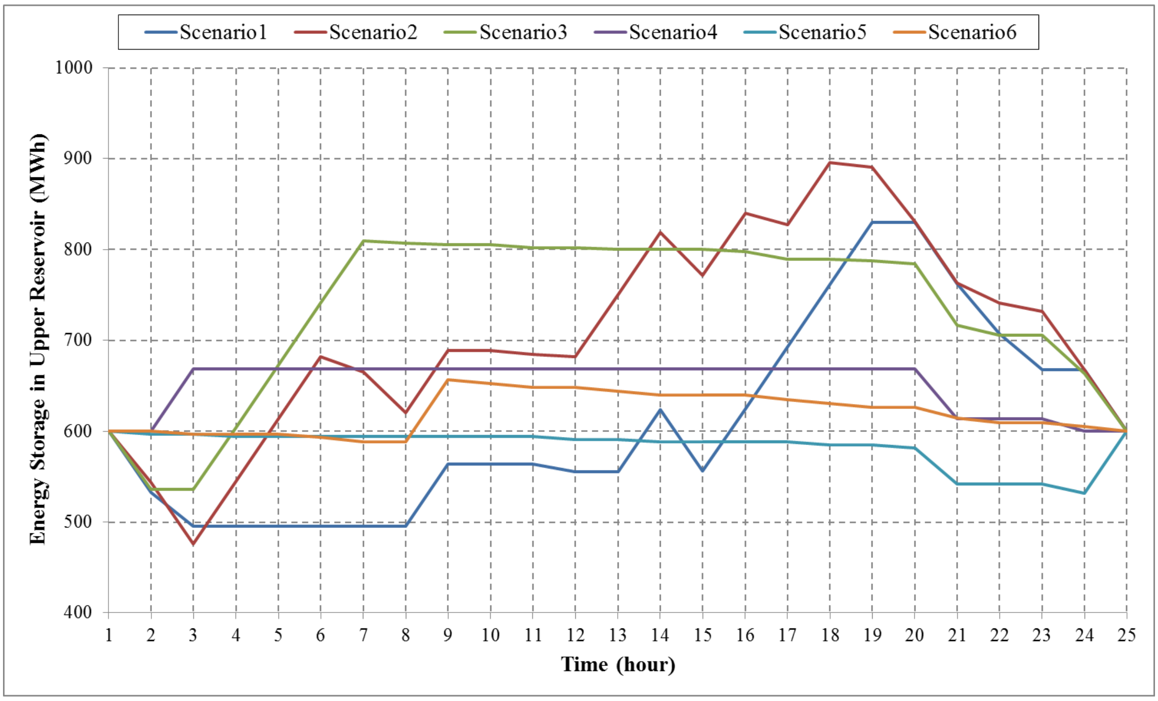


Fig. 3.10: Energy Storage Level in Upper Reservoir (Case-II)

From the Case-II, it has been seen that under 1st and 2nd scenarios, wind-PSP system did not utilize the full wind output to increase the revenue at low market price but used this energy for storage by operating the PSP in pumping mode. This stored energy increased the revenue during high market price by operating the PSP in generating mode. In this case, pumping operation of PSP system depends only on the wind system. In third case, the wind-PSP system integrated with grid to provide the day ahead scheduling, where both the wind system and grid supplied the energy to the PSP for pumping operation. Fig. 3.11 to 3.13, show that grid connected wind-PSP system in Case-III is more successful to reduce the market imbalances as compared to Case-II. This system not only decreased the market imbalance by 40% but also increased the overall revenue by 4% as shown in Table 3.6.

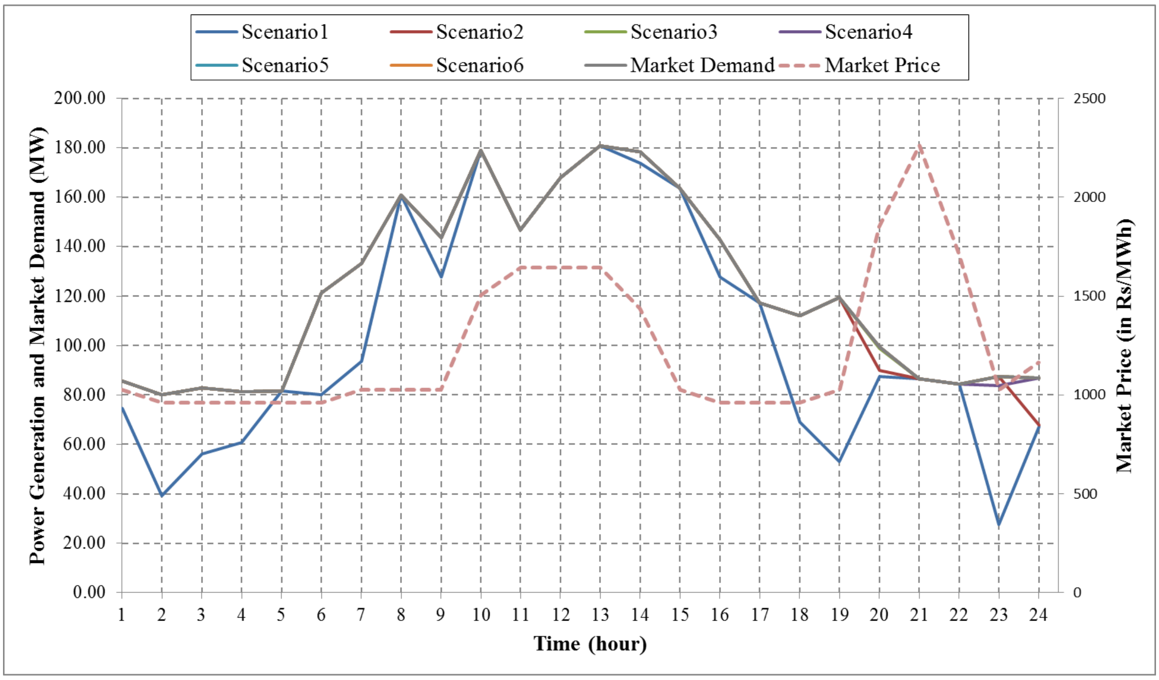


Fig. 3.11: Wind Farm and Pumped Storage Plant Operation (Case-III)

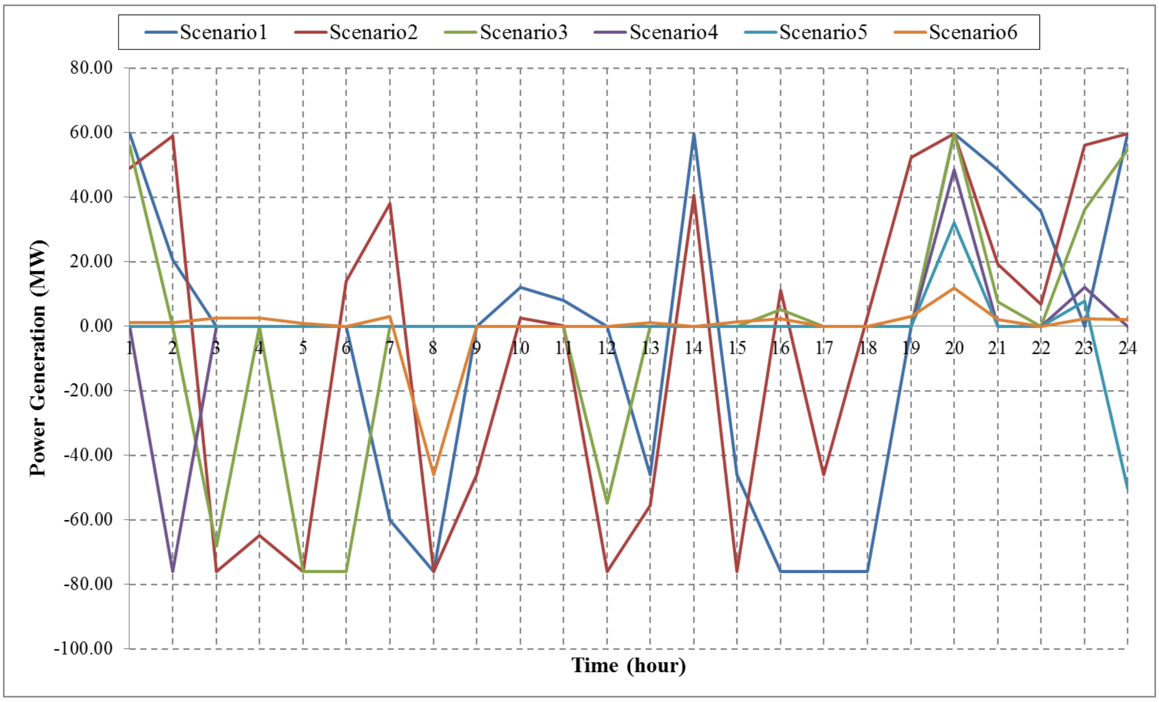


Fig. 3.12: Operation of Pumped Storage Plant (Case-III)

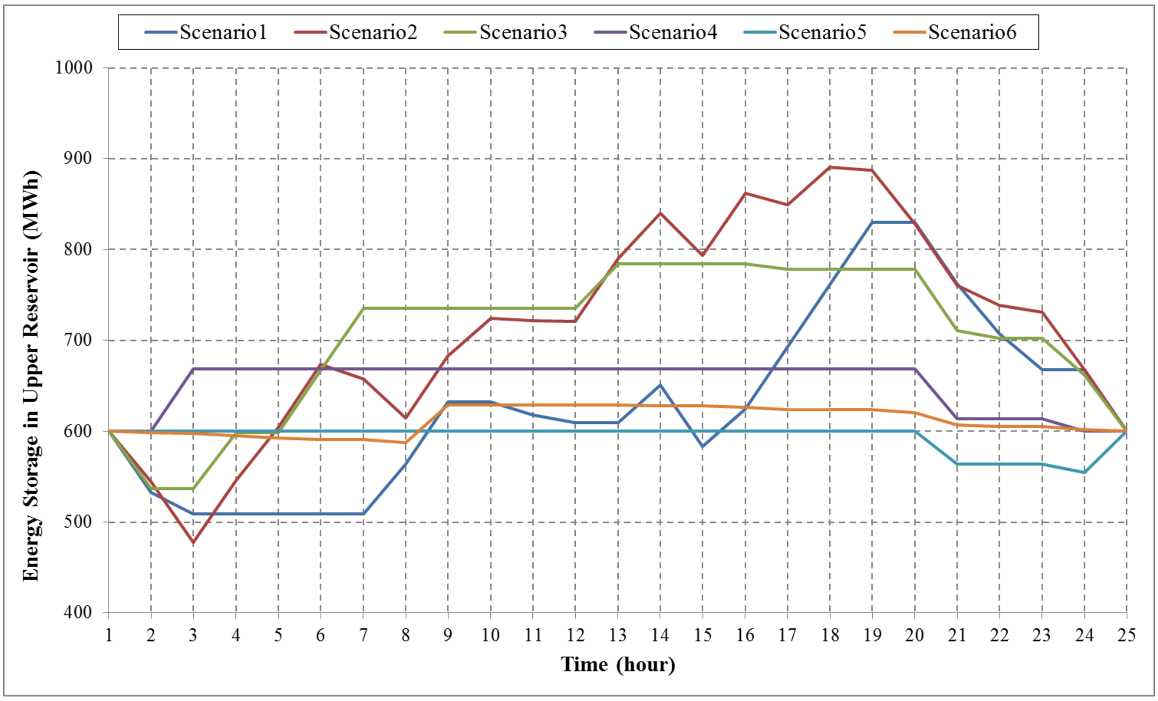


Fig. 3.13: Energy Storage Level in Upper Reservoir (Case-III)

From the above results, it has been found that the Case-III provided the best operation compared to all the other cases (Fig. 3.14). The variable operation of PSP increased the overall profit across the grid connected wind-PSP system.

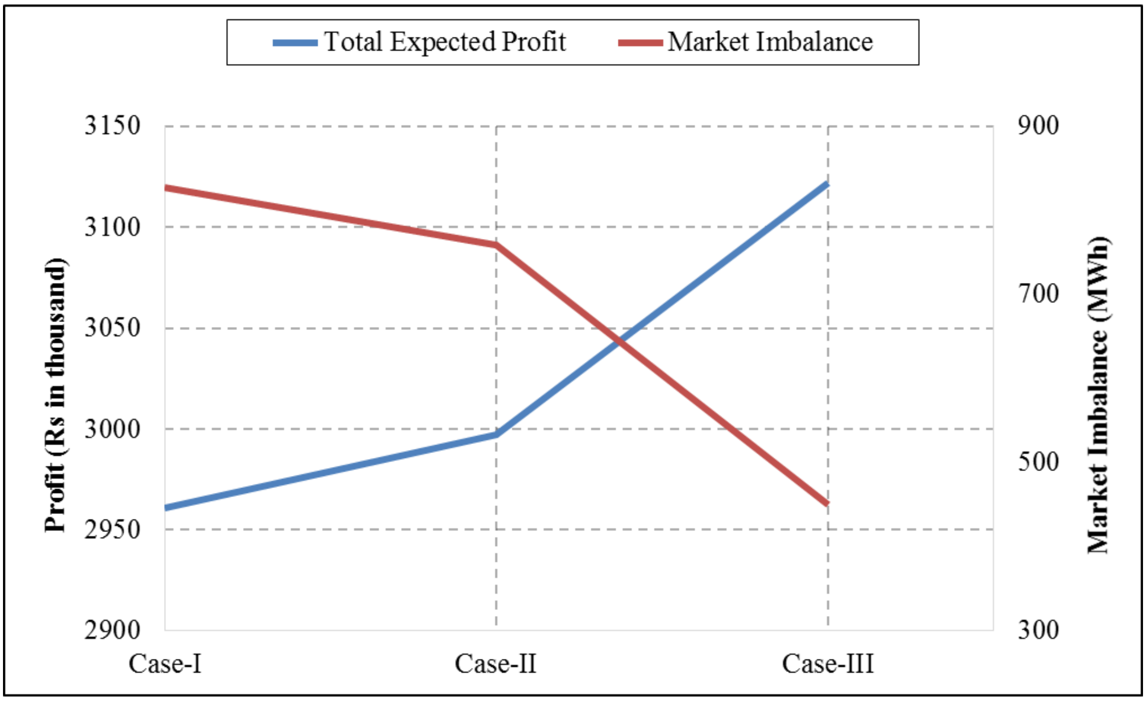


Fig. 3.14: Comparison of profit and market imbalance under different cases

CHAPTER–4

RISK MANAGEMENT OF WIND-PSP SYSTEM

4.1 INTRODUCTION

In the previous chapter, probabilistic forecasting technique has been used to predict the wind uncertainty, though in most of the cases, forecasting results were not very accurate and bring risks in the system. To manage these risks properly, a suitable model is required. Li and Jiang (Li and Jiang 2010, 2011), studied two methods (VaR and IRM) for evaluating risks in the wind energy systems and analysed an economic dispatch problem for wind and thermal power systems. Abreu et al. (2012) provided the combined operation of wind- hydro system in day-ahead market and used the risk-constrained model to reduce the expected downside risk across the wind-hydro system. Gonzalez et al. (2012) analyzed both wind direction and speed type uncertainty risks to find the optimal design of wind farm. Catalao et al. (2012) used two stage stochastic programming approach to maximize the profit from the wind power generation at a given level of risk, where the level of risk has been evaluated using conditional value-at- risk (CVaR) methodology.

In the "trial and error" approach, numbers of experiments are performed to observe the variability or uncertainty of parameters, which affect the output results (Sayuti et al. 2012). Main drawback of this approach is its inability to provide optimum result as well as consumes long time in computation due to large number of experiments (Wei-Chung et al. 2007). Wen-Hsien et al. (2010) recommended the use of Taguchi method to solve the difficulties in the conventional "trial and error" approach. Under this method, many ideas from the statistical experimental design are used for evaluating and implementing improvements in the process for handling the uncertain parameters.

Taguchi (1987) developed a method for designing experiment to improve the quality of a product by reducing the effect of uncertain variable. The idea used for designing the experiment differs from the other conventional experimental design techniques as it investigates the effect of uncertain parameters by considering the both mean and variance of a process performance characteristics. The basic concept of Taguchi methodology is based on the fractional factorial design (Montgomery (1997)). Taguchi method evaluates and implements the improvement in processes, products, facilities and equipment to yield the best result by reducing the number of defects and uncertainties in the design variables. Tsui (1992) gave a review of Taguchi’s robust design methodology. In the last two decades, Taguchi’s method has been applied to a number of design applications and provided the effective results by reducing the number of experiments.

Orthogonal Array (OA) based Taguchi’s method provides a simple design for experiments having large number of variables on few levels (Sibalija et al. 2011). The major objectives of the parameter design based techniques are to minimize the product or process variation and to design flexible and robust products or processes that are adaptable to any environmental conditions.

Although the Taguchi’s method has been proved to be a robust and effective tool for parameter optimization, the main drawback of the Taguchi's method, is that it cannot efficiently handle the presence of several conflicting objectives and constraints that occur under various design environments.

In the present study, a mixed-integer type problem has been formulated to obtain the optimal wind-PSP scheduling under uncertainty. A probabilistic forecasting technique has been used to forecast the uncertainty in the available wind data, however, the results obtained from this technique are not always accurate and cause the deviation in the forecasted and actual availability of the wind data. This deviation can reduce or increase the expected profit and causes risk into the system. The proposed approach maximizes the expected profit across wind-PSP system at the maximum level of the risk. An experimental design technique based on Taguchi method is employed in this study to calculate the risk by computing the loss in the expected profit due to the variation in uncertainty level across each test. The Taguchi method is best used, when there are intermediate number of variables between 3 to 50, few interactions between variables and only few variables contribute significantly. The proposed method utilizes OA based structure, which is easy to implement and uses limited number of experiments thus requires less computational time (Anagnostopoulos and Papantonis 2007). A variable speed type PSP unit has been considered in this problem, which effectively reduces the market imbalances occurred by uncertainties in wind generation.

4.2 WIND-PSP MODEL FOR RISK MANAGEMENT

In this study, uncertainty across the wind data is considered in the form of scenarios. Effect of uncertainty on wind-PSP system has been analyzed by maximizing the total revenue (TR) for the given set of scenarios. A stochastic method is adopted for analysis, considering the wind data as a stochastic variable. In this method, probabilistic factor (π) has been assigned in order to compute the TR for the given set of scenarios.

Similarly, number of test cases has been considered and each case is defined with different set of scenarios. The Taguchi method is applied to select the appropriate combination of scenarios based on the results obtained from the stochastic method. In this method, OA structure is used to select the best level of scenarios on the basis of maximum risk.

Here, 24 hours time frame has been considered for scheduling of wind and PSP under day-ahead market, where both wind and pumped storage systems operated as single entity, even not necessarily installed at the same or adjacent location. Both the systems (wind and PSP) are connected with the grid. To utilize the power generated by wind and PSP efficiently as per the demand or bid received from the electricity market, a strategy is developed to store wind energy in the upper reservoir by pumping action of PSP during the low demand period. In case, wind power plant is unable to supply the required power to PSP during the pumping mode, the required power for pumping is drawn from the grid. For this mixed integer type problem, stochastic approach has been used to determine the optimal hourly scheduling of power generation by wind and PSP to reduce the effect of wind data uncertainty. These entities operated in grid connected day-ahead market to increase the overall profit under given market price.

4.2.1 Objective Function

In the market based system, wind-PSP operation is always effected from the system uncertainty. So, a probabilistic forecasting technique is used to predict the wind uncertainty in the form of scenarios as given in section 3.2. An experimental design technique based on Taguchi method is used to select the level from the given set of scenarios (*S*) that provided the maximum risk to the system. The objective function for this problem is to maximize the total revenue obtained from the wind-PSP system under these selected set of scenarios to provide the stable operation under maximum risk as given in Eq. (4.1).

$$\text{Maximize Profit: } \sum_{S}\sum_{t=1}^{T}\pi(t,s)\left(R_{psp}(t,s)+R_{wind}(t,s)-R_{loss}(t,s)\right) \tag{4.1}$$

In Eq. (4.1), *S* is set of different scenarios S_1, S_2, S_3, ..., S_{Ns} as obtained from the OA structure as described in section (4.3) and *T* is the total time period. $R_{psp}(t,s)$ and $R_{wind}(t,s)$ are the total revenue obtained from the PSP and wind system respectively as given in Eq. (3.9 - 3.12). $R_{loss}(t,s)$ is the revenue loss or the penalty imposed by the market for creating imbalance between generation and demand as given in Eq. (3.13). The objective function as given in Eq. (4.1) has been optimized subjected to various equality and inequality constraints as defined in section (3.3.3).

4.3 TAGUCHI'S ORTHOGONAL ARRAY MODEL

For managing risk across the wind-PSP system, it is required to find the level of risk across each scenario. One of the major advantages of using risk management strategies across the wind-PSP system is to build the system for bearing the risk during day-ahead market scheduling. An orthogonal array is a matrix that is represented by $L_r(B)^{Ns}$. *r* and *Ns* are representing the number of rows and columns of OA respectively.

Total numbers of testing *r* in the Taguchi method are decided by OA, which depends on the value of *Ns* and *B* (varying level across each scenario) as used in the systems (Liu and Cai 2005; Yu and Rosehart 2012).

According to Fraley et al. (2007) the proper OA L_r can be selected using the array selector table as given in Table 4.1, after knowing the number of variable *Ns* and *B* is the varying level across each scenario. This array selector table was created using an algorithm developed by Taguchi and allowed each variable and setting to be tested equally (Ross 1996). For the given wind-PSP system, S_1, S_2, S_3……..S_{Ns} are the scenarios representing the wind uncertainty. Each scenario is selected within the two given upper and lower level as shown in Fig. 4.1 and 4.2 and presented in Table 4.2 as *L* (Low) and *H* (High). The algorithm for applying the Taguchi method for wind-PSP system is described as follows:

i. Initially, it is required to determine the number of uncertain variables or scenarios. These variables predict the actual availability of wind data for the given time period. This data is used to evaluate the total revenue (TR) across the wind-PSP system. Six number of scenarios have been considered in this study.
ii. Each scenario varied between the two levels *L* (*Low*) and *H* (*High*). The variations affect the value of *TR* across each scenario.
iii. Orthogonal arrays indicate the effect of variation in each scenario between the low and high levels. Number of testing in the OA depends upon the number of scenarios selected (*Ns*) and the variation level across each scenario (*B*). Taguchi method has been applied with a $L_8(2)^6$ OA, where the number of testing levels are 8 as given in Table 4.2.
iv. After each test, total revenue can be found across wind-PSP system for each scenario. The main objective of this analysis is to maximize the revenue across each scenario as given in Eq. 4.1. Stochastic programming based technique has been used to obtain the optimal value of the solution by satisfying the constraints given in section 3.3.3. Each set of scenario has provided the individual solution. In

order to achieve a single solution, average sum of each individual solution has been determined.

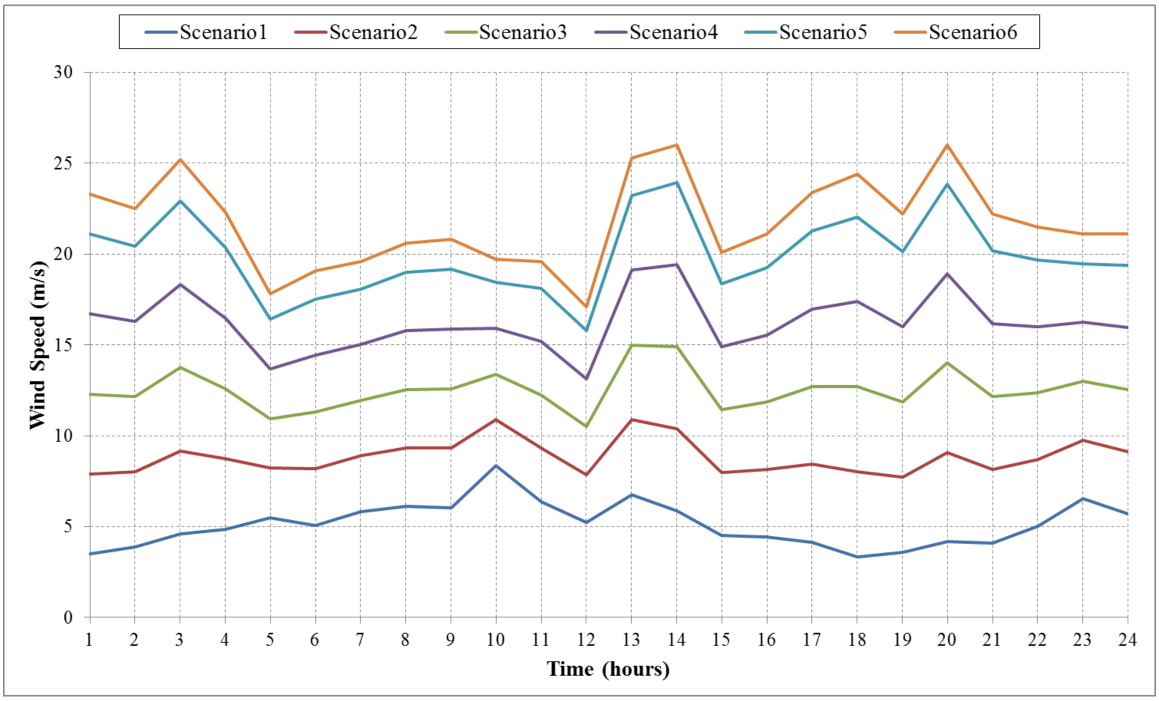


Fig. 4.1: Upper wind speed limits for six different scenarios

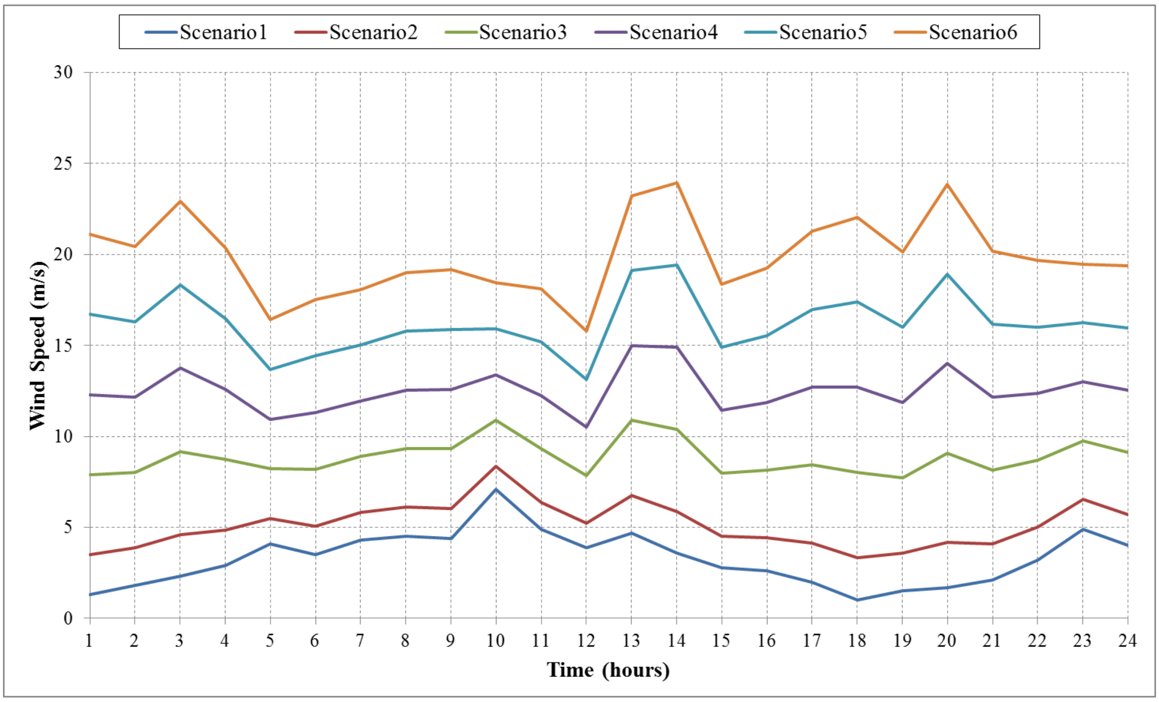


Fig. 4.2: Lower wind speed limits for six different scenarios

v. The above technique applied to each test case in order to increase the revenue across each test, where (*TR1, TR2….TR8*) are the total revenue of each test level as given in Table 4.2.

vi. To observe the effect of varying level in wind-PSP system, each scenario is divided into two groups. First and second groups are associated with low and high levels respectively and average value (*Avg*) across each group has been computed. For example, average value of *TR* across 4th scenario has been calculated as given in Eq. (4.2) and Eq. (4.3), representing the *Avg* for Low and High levels respectively. Variation of each *Avg* value (*dA*) across the respective scenario has been computed to demonstrate the effect of variation of level in wind-PSP system as shown in Table 4.3.

$$Avg\_L4 = (TR1 + TR3 + TR5 + TR7)/4 \tag{4.2}$$

$$Avg\_H4 = (TR2 + TR4 + TR6 + TR8)/4 \tag{4.3}$$

$$dA4 = Avg\_L4 - Avg\_H4 \tag{4.4}$$

Table 4.1: Orthogonal Array selector table

No. of Level (B)	No. of Variables or Scenarios (N_s)								
	2	3	4	5	6	7	8	9	10
2	L_4	L_4	L_8	L_8	$\mathbf{L_8}$	L_8	L_{12}	L_{12}	L_{12}
3	L_9	L_9	L_9	L_{18}	L_{18}	L_{18}	L_{18}	L_{27}	L_{27}
4	L_{16}	L_{16}	L_{16}	L_{16}	L_{32}	L_{32}	L_{32}	L_{32}	L_{32}
5	L_{25}	L_{25}	L_{25}	L_{25}	L_{25}	L_{50}	L_{50}	L_{50}	L_{50}

Table 4.2: Structure of $L_8(2)^6$ Orthogonal Array (OA)

No of Testing	Scenarios – Uncertain Variables						Total Revenue
	S_1	S_2	S_3	S_4	S_5	S_6	
1	L1	L2	L3	L4	L5	L6	TR1
2	L1	L2	L3	H4	H5	H6	TR2
3	L1	H2	H3	L4	L5	H6	TR3
4	L1	H2	H3	H4	H5	L6	TR4
5	H1	L2	H3	L4	H5	H6	TR5
6	H1	L2	H3	H4	L5	H6	TR6
7	H1	H2	L3	L4	H5	L6	TR7
8	H1	H2	L3	H4	L5	L6	TR8

Table 4.3: Test Response of OA

Level	Scenarios – Uncertain Variables					
	S_1	S_2	S_3	S_4	S_5	S_6
L	Avg_L1	Avg_L2	Avg_L3	Avg_L4	Avg_L5	Avg_L6
H	Avg_H1	Avg_H2	Avg_H3	Avg_H4	Avg_H5	Avg_H6
dA	dA1	dA2	dA3	dA4	dA5	dA6

4.4 RESULTS AND DISCUSSIONS

The details of the wind-PSP system considered in this study have been given in Table 3.2. For each test case, wind energy system combined with PSP is operated to increase the total revenue or profit across the market in case studies I and II respectively. For the PSP unit, the size of upper reservoir has been taken as 1200 MWh subjected to the condition that its initial and final level during the 24 hour period should be same, so that the size of reservoir easily reflects to any of the practical case. Both wind and PSP supply the power to the market at the given market price. PSP draws the power from the grid for pumping at given market price whereas pumping uses wind power at constant given price of *Rs* 548 per MWh. Grid based pumping energy cannot be more than 300 MWh with the maximum power capacity limit of 100 MW as shown in Table 3.2. The analysis was carried out using commercial solver KNITRO for this MINLP type problem.

Two different cases have been considered to prove the optimality of the solution. In the first case, scheduling of wind-PSP system was carried out without considering the uncertainty risk. For this stochastic mixed integer type problem, stochastic wind data has been considered to determine the wind uncertainty. This stochastic wind data has been divided into six different scenarios. In the optimization process, the wind power output across each scenario remains fixed at its forecasted value. Stochastic approach has been applied to introduce the effect of wind data uncertainty and the solution is optimized to increase the overall profit by satisfying the market demand.

The wind-PSP system is integrated with the grid to provide the day ahead scheduling, where the both wind plant as well as grid supplied the energy to the PSP for pumping operation. Fig. 4.3 to 4.5, show that grid connected wind-PSP system seem to be more successful to reduce the market imbalances under uncertainty. The variable operation of PSP increases the overall profit across the grid connected wind-PSP system. During 1st, 2nd, and 3rd scenarios the power generated by wind-PSP system is low, thus the imbalance cost during these scenarios are very high as compared to the other scenarios as shown in Table 4.7. Under these three scenarios, maximum pumping has been provided to utilize the stored energy by generating between 19 and 22 hours, when the market price is high. Under the other three scenarios, wind power mostly seem sufficient to supply the market demand, required less pumping operation and tried to increase the overall revenue. As shown in Table 4.6, the overall profit of wind-PSP system is *Rs* 3121.82 thousand.

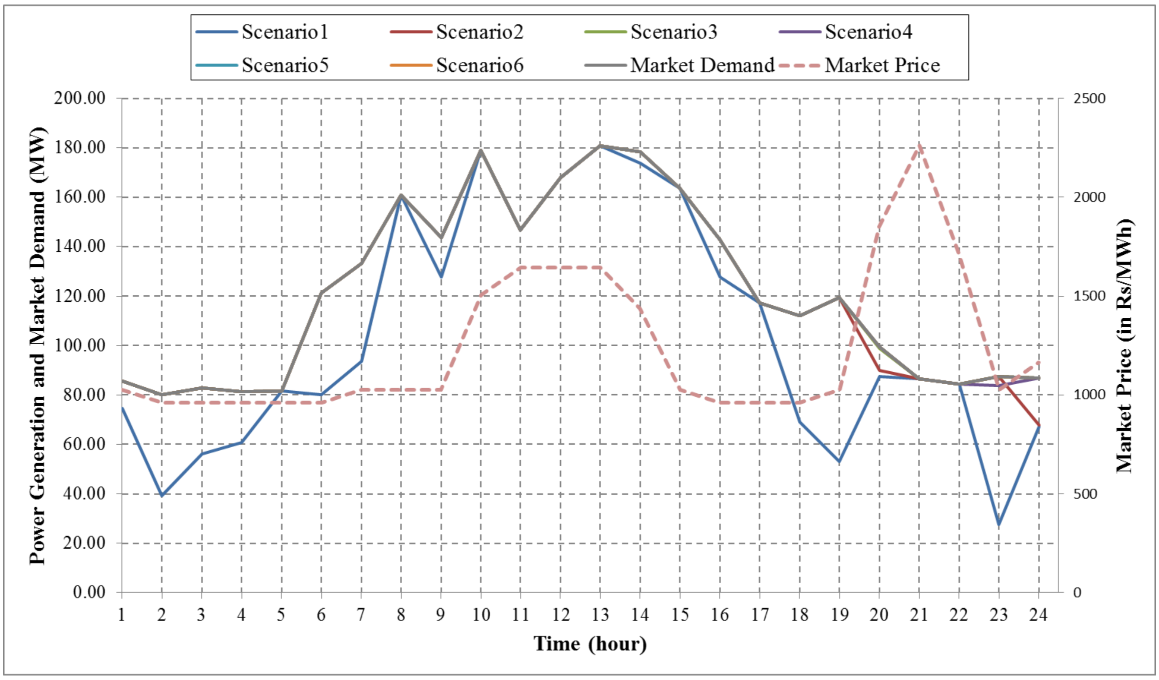


Fig. 4.3: Wind and pumped storage plant operation (Case-I)

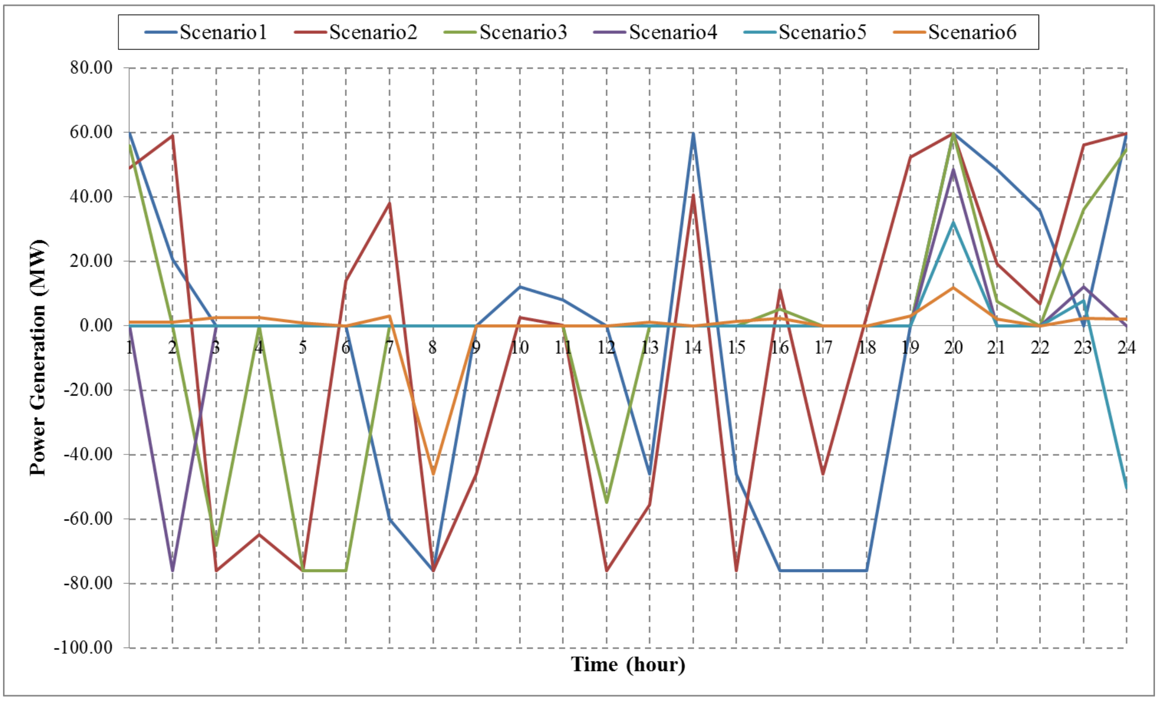


Fig. 4.4: Operation of pumped storage plant (Case-I)

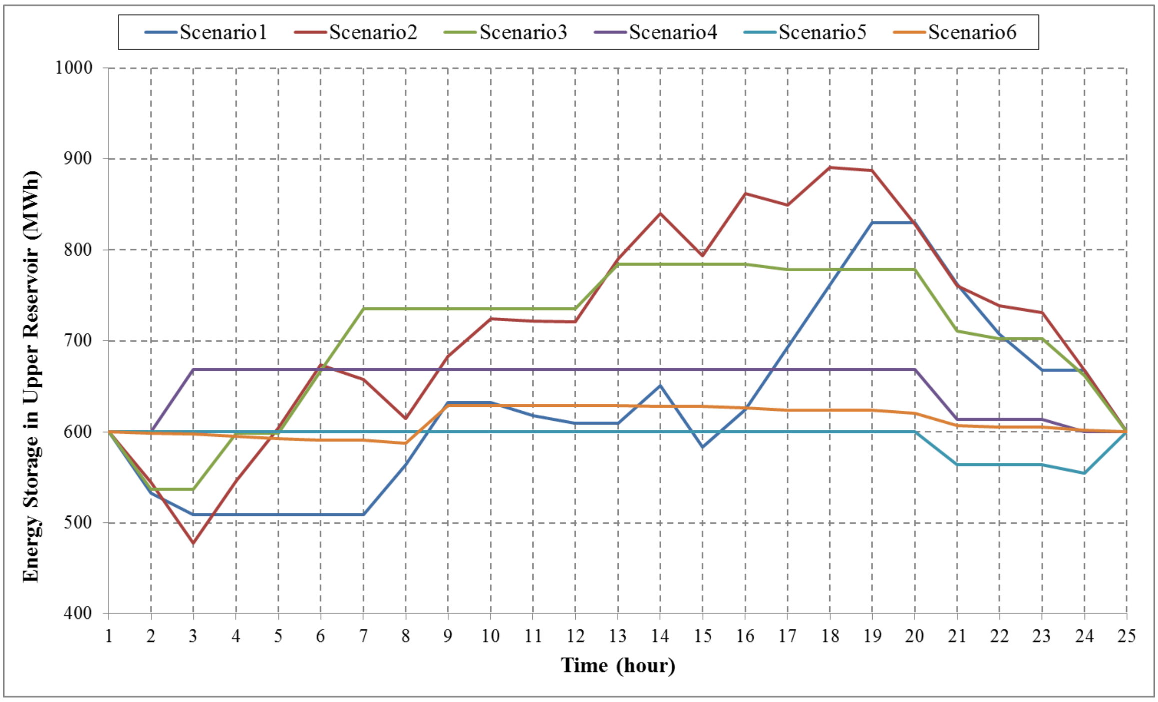


Fig. 4.5: Energy storage in upper reservoir (Case-I)

In the second case, scheduling has been done considering the uncertainty risk across the wind-PSP system. Two levels referred as high and low have been selected for each scenario, as given in Table 4.2. For each test case, wind system is operated with PSP to increase the total revenue or profit across the market.

After optimizing the wind-PSP system for each set of scenario, the profit across all the eight experiments with uncertain variable is presented in Table 4.4. It has been found that with the variation in wind speed for each scenario, the profit for wnd-PSP system varied up to 34%. For stability of the system, it is required to know the maximum occurrence of the risk across the wind-PSP system. This risk is referred as the loss of the profit with the variation of wind data. The average profit across each scenario for the different level (*H* and *L*) of uncertainty is presented in the Table 4.5. The risk in the form of loss in profit as given in Table 4.5 is the difference of average profit across the level *H* and *L*. The value of risk indicates the influence of each factor discovered by the experiments. Negative (-*ve*) values indicate the reduction in risk as obtained from scenario S_1, S_2, S_3, S_4, S_5 (e.g. -77762, -359447, -154328, -3287, -158 respectively) and positive (+*ve*) values indicate the increase in the risk as acquired from S_6 (e.g. 70671) as shown in Fig. 4.6. From the Table 4.5, it is seen that the maximum risk has been under scenario S_1, S_2, S_3 and S_4 set to level *L*, while S_5 and S_6 are set to level *H*. The set of scenarios, which attain maximum risks are mentioned as *L1*, *L2*, *L3*, *L4*, *L5* and *H6*. Fig. 4.7 and Fig 4.8 show the generation scheduling of wind-PSP system for these scenarios.

Table 4.4: Orthogonal Array with Test Result

No of Testing	Scenarios – Uncertain Variables						Total Revenue (in thousand *Rs*)
	S_1	S_2	S_3	S_4	S_5	S_6	
1	L1	L2	L3	L4	L5	L6	1184.66
2	L1	L2	L3	H4	H5	H6	1117.41
3	L1	H2	H3	L4	L5	H6	1627.74
4	L1	H2	H3	H4	H5	L6	1701.88
5	H1	L2	H3	L4	H5	L6	1416.89
6	H1	L2	H3	H4	L5	H6	1349.36
7	H1	H2	L3	L4	H5	H6	1551.35
8	H1	H2	L3	H4	L5	L6	1625.13

Table 4.5: Risk or profit loss across each scenario

LEVEL	Revenue across each scenario (in thousand *Rs*)					
	S_1	S_2	S_3	S_4	S_5	S_6
L	1407.92	1267.08	1369.64	1445.16	1446.72	1482.13
H	1485.68	1626.53	1523.97	1448.44	1446.88	1411.47
Risk or Profit Loss (L – H)	-77.76	-359.45	-154.32	-3.28	-0.16	70.67
RANK	4	6	5	3	2	1
Optimal Set	L1	L2	L3	L4	L5	H6

Table 4.6: Total expected profit for all cases

Cases	Total Expected Profit (thousand *Rs*)
Without considering the risk	3121.82
With considering the risk	1114.23

From Fig. 4.7 and Fig. 4.8, it is seen that PSP units are scheduled to generate power during the periods of high market price. It is also observed that, this scheduling reduced the imbalance between the generation and demand, thus avoided penalty during high market price for difference in demand and supply.

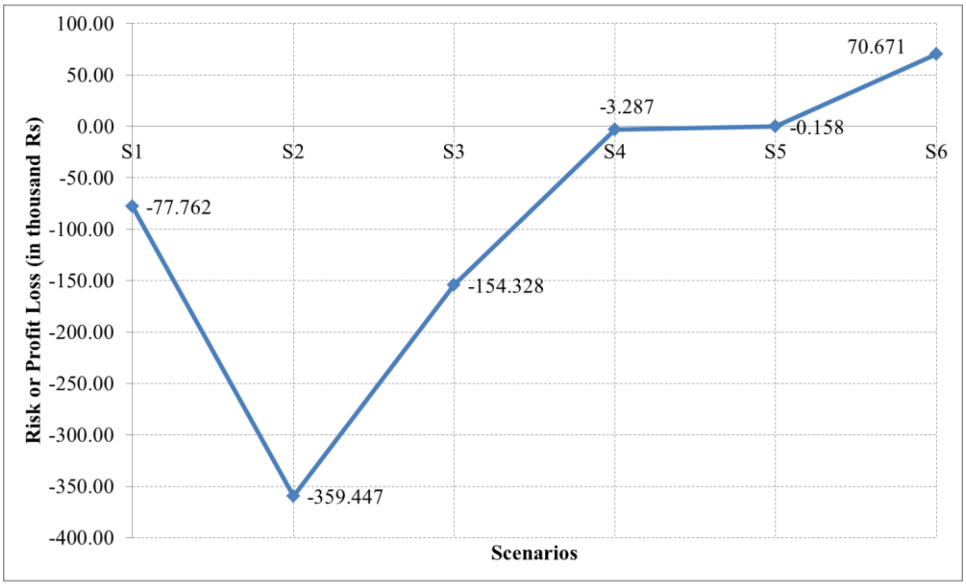


Fig 4.6: Risk or profit loss across six different scenarios

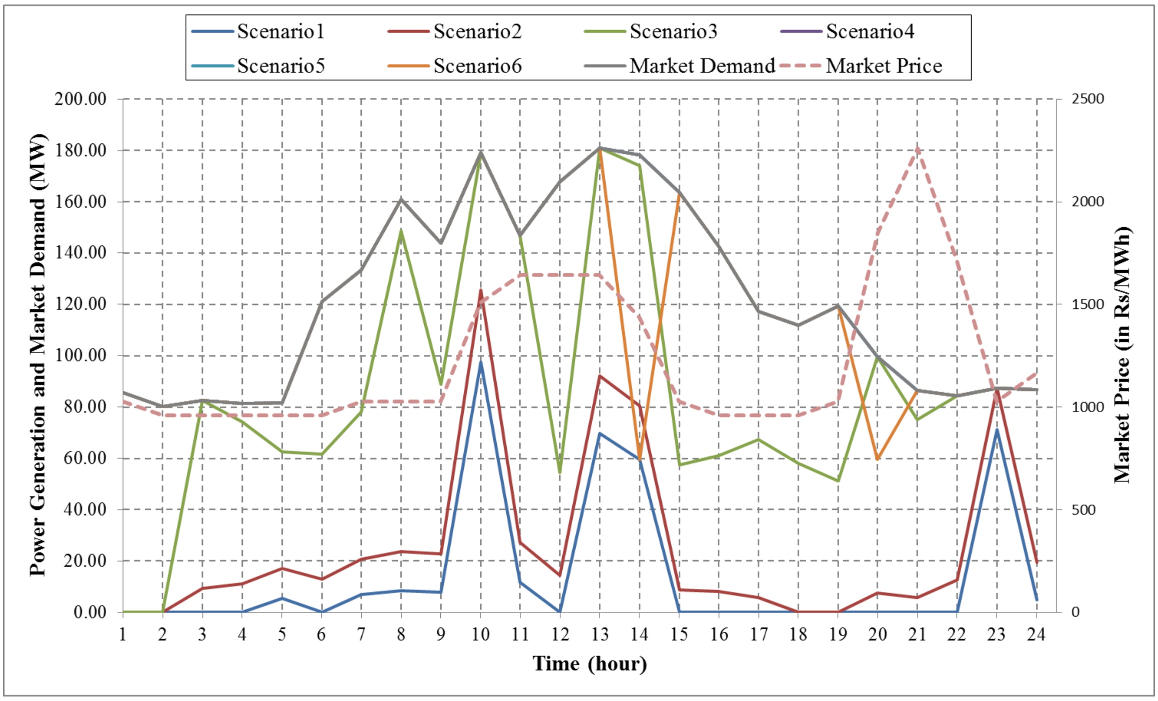


Fig. 4.7: Wind and pumped storage plant operation (Case-II)

During 1st, 2nd and 3rd scenarios, wind power output is very low causing high market imbalance and utilizing more grid power compared to others scenarios. However, during 4th, 5th and 6th scenarios, wind power output is very high, thus market imbalance becomes very low as shown in Fig. 4.8, where all these three scenarios are overlapping with the market demand curve. Under all six scenarios, pumping operation has been provided in such a way that it kept the initial reservoir level equal to the final level at the end of wind-PSP scheduling as shown in Fig 4.9. Table 4.7 illustrates the results for selected set of scenarios, where generation revenue represents the market imbalance from the combined operation of wind and PSP plant.

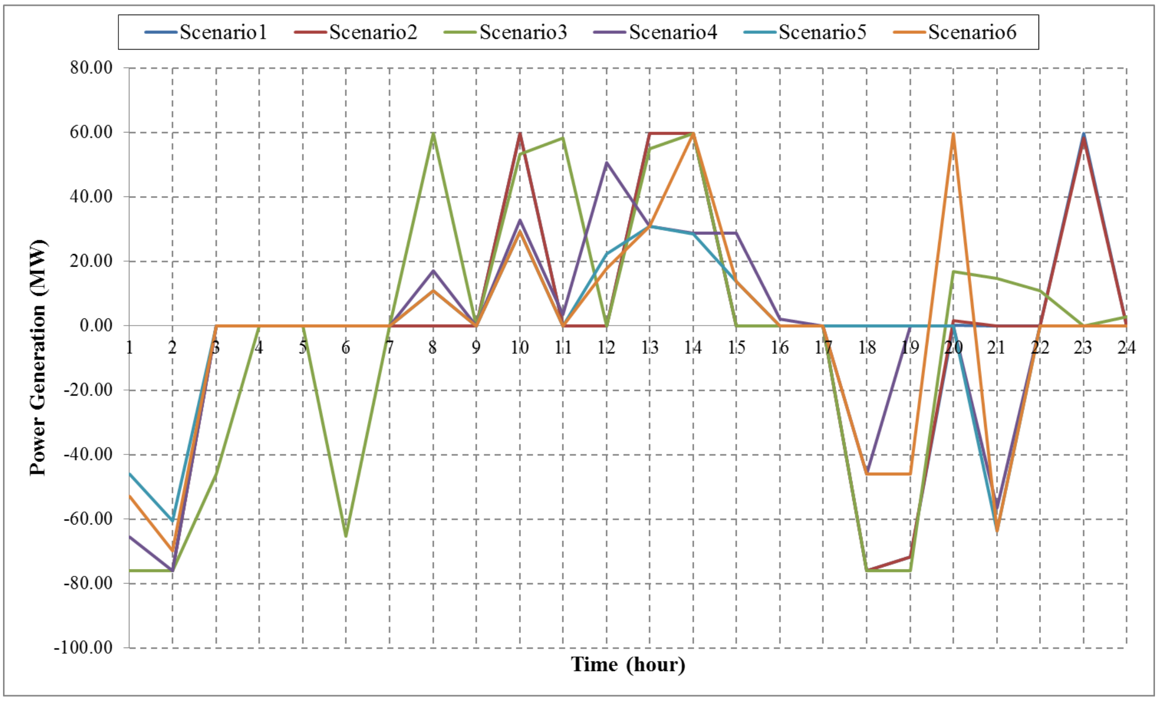


Fig. 4.8: Operation of pumped storage plant (Case-II)

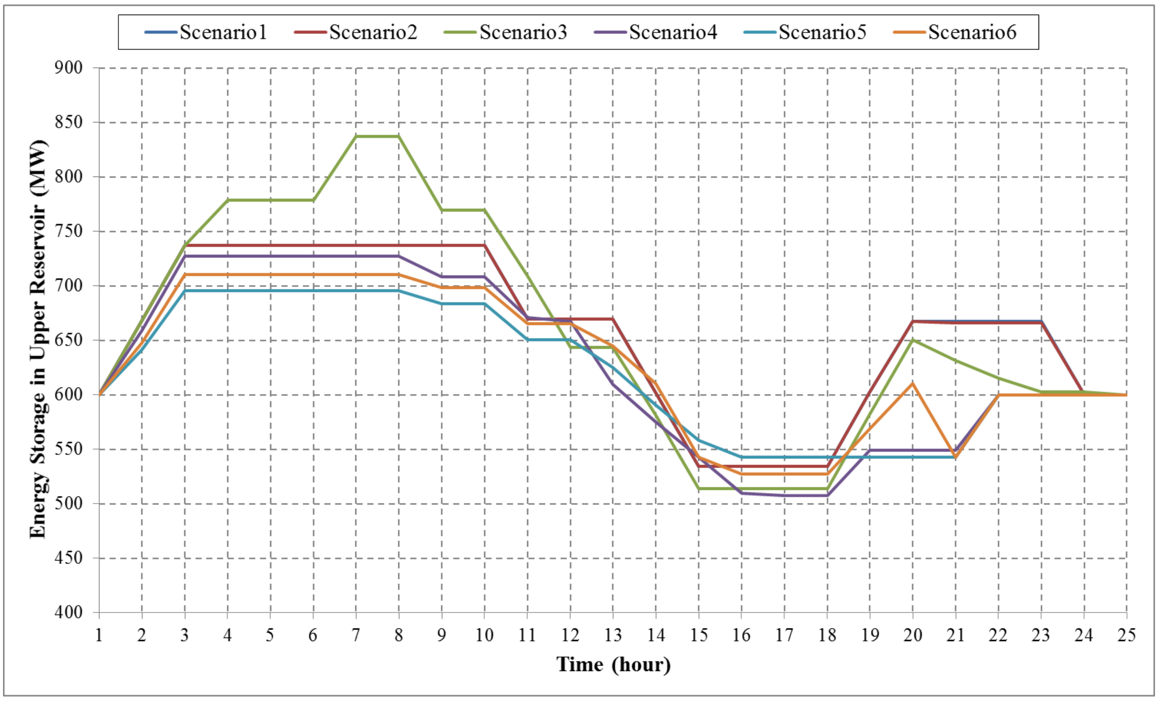


Fig. 4.9: Energy storage in upper reservoir (Case-II)

The comparison of result for both cases, with and without risk has been presented in Table 4.6 to 4.8. The effect of uncertainty has been considered in both the cases. It has been seen that the result provided by Case-I are not very accurate and there is still some risk available. This drawback has been reduced in Case-II with the introduction of Taguchi based risk management technique. For the Case-II, the performance of wind-PSP scheduling at maximum risk availability has been presented in Table 4.6, 4.7 and 4.8 representing the effect on total expected profit, total market imbalance and the total wind utilization respectively. As given in Table 4.6, maximum profit across the wind-PSP system at the maximum risk has been reduced by 64% in Case-II as compared to the Case-I (without considering the risk). It not only increased the market imbalance but also reduced the wind utilization across the system as shown in Table 4.7 and 4.8 respectively. One of the major advantages of this approach is to design a wind-PSP system, which is able to withstand any level of risk and provide the stable performance under uncertain condition.

Table 4.7: Market imbalances across each scenario

Scenarios	Total Market Imbalances (MWh)	
	Without considering the risk	With considering the risk
1	417.12	2579.36
2	28.65	2309.74
3	0.76	862.47
4	3.69	0.0
5	0.0	0.0
6	0.0	158.62

Table 4.8: Wind energy utilization by each scenario

Scenarios	Wind Utilization in Revenue (MWh)	
	Without considering the risk	With considering the risk
1	2142.91	105.08
2	2422.94	374.69
3	2703.45	1730.03
4	2858.91	2728.78
5	2883.14	2787.72
6	2886.52	2542.87

CHAPTER–5

GAME THEORY BASED SCHEDULING OF WIND AND PUMPED STORAGE SYSTEM

5.1 INTRODUCTION

From the studies presented in chapters 3 and 4, it can be 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. None of the models developed in the past were able to reduce the effect of the uncertainty in the wind-PSP system. In these models probability distribution technique has been used but those are not able to estimate the exact amount of uncertainty available in the system.

For dealing with different sources of uncertainty, game theory based models have 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, game theory-based approaches have been used to analyze the natural behavior of deregulated market. Kannan et al. (2010) used this model to analyze the various dynamic and static impact of system on the market under the uncertain condition. Miglivacca et al. (2006) used the game theory based model to analyze the effect of market competition in the simulator for providing the long term simulation. Different game theory based models have been used for designing the optimal bidding strategy under the electricity market (Ceppi et al. 2010 and Song et al. 2002). Ming et al. (2010) provided the risk analysis on the offshore wind farm consisting of various steps like risk identification, risk measurement and risk allocation. For the analysis, Nash equilibrium technique has been used, which effectively controlled the risk and attained the greatest overall benefit. However, in this study, real system was not analyzed. The simple way of using this technique is adopting the worst-case solution to make the optimization problem insensitive to variation in input data. This approach, however, can be considered as a conservative and delivering a very high cost solution.

Game theory based Min-Max optimization method is used to reduce the effect of uncertainty during the scheduling of Wind-PSP System. This method provides the worst case performance of the system under uncertain conditions. Two types of uncertainties have been considered under this problem:

i. **Uncertainty in wind data:** The uncertainty of wind data is available as stochastic variable and presented in the form of scenarios to find out the uncertainty across the wind system. Probabilistic model has been used for generating these scenarios as described in section 3.2. In this model, 24 hours wind speed data has been divided in to 24 segments and each hourly segment further divided into *Ns* discrete segments, where *Ns* is the number of scenario. Thus different scenarios (s_1, $s_2 \ldots s_{Ns}$), have been generated using these discrete states as given in Eq. 5.1.

$$\tilde{P}^{s}_{wind}(\mathrm{t}) \qquad \text{where } s \in \{s_1, s_2, s_3 ....s_{Ns}\} \tag{5.1}$$

where, value of $\tilde{P}^{s}_{wind}(\mathrm{t})$ is given in the form of scenarios. Actual value of wind generation can be represented in the form of fixed planned value $\bar{P}_{wind}(\mathrm{t})$ and variable or uncertain value of generation $\Delta\tilde{P}_{wind}(\mathrm{t})$ as given in Eq. 5.2.

$$\tilde{P}^{s}_{wind}(\mathrm{t}) = \bar{P}_{wind}(\mathrm{t}) + \Delta\tilde{P}_{wind}(\mathrm{t}) \tag{5.2}$$

ii. **Uncertainty in market demand:** A typical uncertainty in the market demand is shown in Fig 5.1 and has been considered in the form of deterministic variable and represented by the minimum and maximum interval as shown in Eq. 5.3, where the market demand $\tilde{P}d$ is the deterministic variable representing the market demand uncertainty.

$$Pd_{\min} \le \tilde{P}d(\mathrm{t}) \le Pd_{\max} \tag{5.3}$$

where $Pd_{\min}$ and $Pd_{\max}$ are the minimum and maximum demand limits across the market respectively. The uncertainty in market demand may also written as Eq. 5.4.

$$\tilde{P}d(\mathrm{t}) = \bar{P}d(\mathrm{t}) + \Delta\tilde{P}d(\mathrm{t}) \tag{5.4}$$

where, $\bar{P}d(\mathrm{t})$ is the planned value of market demand and $\Delta\tilde{P}d(\mathrm{t})$ is the demand variation across the market.

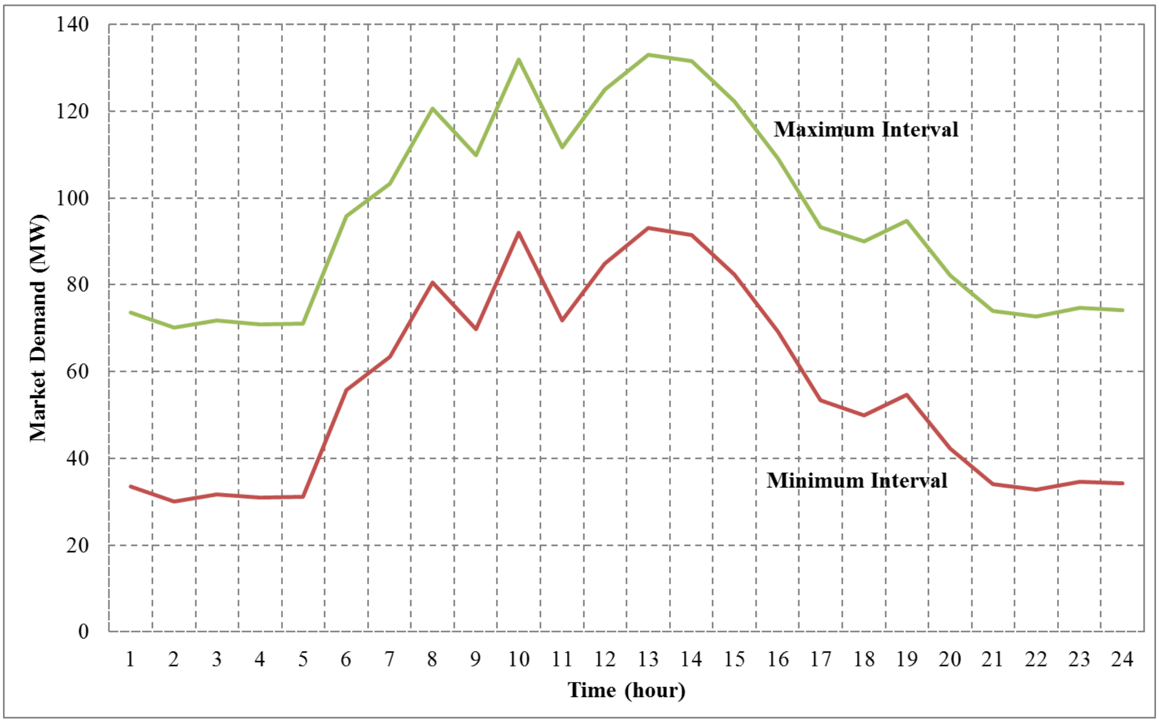


Fig. 5.1: Market demand

These types of uncertainties are difficult to model since both uncertain parameters do not have a known probabilistic distribution. The uncertainty is expressed in the form of variation of parameters that will be modified in a certain magnitude which affect 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. Two different types of PSP operation have been considered here as described below:

Case-I: PSP is operated as conventional pumping unit and hydro generating unit where the pumping operation is carried at a fixed speed.

Case-II: Variable speed pumped storage unit is used to provide the variable pumping operation. Both generation and pumping operations are carried between their given minimum and maximum speed limits.

5.2 PROBLEM FORMULATION AND MODELS

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

5.2.1 Optimization model for wind and PSP system

The main objective of this mixed-integer type problem is to minimize the power imbalance cost F_{min}, during Wind-PSP operation as given in Eq. 5.5.

5.2.1.1 Objective Function

$$F_{\min} = \min_{P_{gen}} \sum_{t \in T} \left(I_{\cos t}(P_{gen}(t), \bar{P}_{wind}(t), \bar{P}d(\mathrm{t}) \right) \tag{5.5}$$

where

$$I_{\cos t}(P_{gen}(t), \bar{P}_{wind}(t), \bar{P}d(\mathrm{t})) = P_{loss}(t) \times \lambda_{mkt} \tag{5.6}$$

$$P_{loss}(t) = \bar{P}d(\mathrm{t}) - Pw_{mkt}(t) - (s(t) \times P_{gen}(t)) \tag{5.7}$$

Problem formulation presented as Eq. 5.5 to 5.7 determine the operation of wind-PSP system. I_{cost} is defined as the product of total power imbalance P_{loss} and market price λ_{mkt} at t^{th} hour (as given in Eq. 5.6). The power imbalance is the difference between the total generation of the system and power consumed by market demand (as given in Eq. 5.7). 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.

5.2.1.2 Constraints

Above objective function is subjected to various constraints as given in Eq. 5.8 to 5.14.

5.2.1.2.1 PSP generation limits

$P_{gen}(t)$ is the power generated by PSP at t^{th} time. $P_{gen}^{\min}$ and $P_{gen}^{\max}$ restrict the power generation between maximum and minimum limits respectively and is shown in Eq. 5.8.

$$P_{gen}^{\min} \le P_{gen}(t) \le P_{gen}^{\max} \tag{5.8}$$

5.2.1.2.2 Imbalance Constraint

$P_{loss}(t)$ represents the total imbalance in the market, which implied that the total generation provided by the market is always equal to or less than the total demand across the market, to avoid the over generation of power in the market (Eq. 5.9).

$$P_{loss}(t) \ge 0 \tag{5.9}$$

5.2.1.2.3 Pumping Power Constraint

For the pumping operation, the PSP can take the power from the wind power plant. For each case, different type of pumping operation has been provided and defined as the Eq. 5.10 and 5.11.

For Case I

$$Pp(t) = Pp_{\max} \tag{5.10}$$

For Case II

$$Pp_{\min} \le Pp(t) \le Pp_{\max} \tag{5.11}$$

5.2.1.2.4 Energy storage equation

The energy balance in the upper reservoir is represented by Eq. 5.12. At the beginning of $(t+1)^{th}$ hour, the energy in the upper reservoir is the sum of initial level in the reservoir at t^{th} hour, $Pp_t^s \times \eta_p$ is the energy supplied to the upper reservoir during pumping mode and Ph_t^s / η_t is the energy generated from the upper reservoir during generation mode. Δt is the time deviation or the time interval between each period, η_p and η_t are the efficiency of pumped storage plant during pumping and generation modes respectively.

$$E(t+1) = E(t) - \Big(\big(P_{gen}(t) \times s(t) \big) / \eta_t - \big(Pp(t) \times (1 - s(t)) \big) \times \eta_p \Big) \times \Delta t \qquad (5.12)$$

5.2.1.2.5 Upper reservoir limits

The energy stored in the upper reservoir *E(t)* has upper and lower limits as given in Eq. 5.13.

$$E_{\min} \le E(t) \le E_{\max} \qquad (5.13)$$

5.2.1.2.6 Wind power constraints

The total power generated by the wind power plant is $\bar{P}_{wind}(t)$ as given in Eq. 5.14, which utilized by the $Pw_{mkt}(t)$ for supplying the power to the market demand and *Pp(t)* for the pumping operation.

$$\bar{P}_{wind}(t) \ge Pw_{mkt}(t) - Pp(t) \times (1 - s(t)) \qquad (5.14)$$

5.2.1.3 Control Variable

This control variable provides the switching of PSP unit between the generating and pumping mode and does not allow both the operation at the same time and given as Eq. 5.15.

$$s(t) \in \{0,1\} \qquad (5.15)$$

5.2.2 Min-max optimization model

5.2.2.1 Objective Function

The objective of this Min-Max optimization model is to min-max the risk R to provide best performance under the uncertain condition as shown in Eq. 5.16. Risk $R(\bar{P}_{gen}, \tilde{P}^{s}_{wind}, \tilde{P}d)$ is caused by the uncertainty in wind data and the market demand. In this model $\tilde{P}^{s}_{wind}$ 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 (5.2.1). Optimal conditions for the controllable variables in min-max model have been resolved while satisfying the various constraints given in Eq. 5.8 to 5.13 and 5.20 to 5.22.

$$\min_{\bar{P}_{gen}} \max_{\tilde{P}^{s}_{wind}, \tilde{P}d} R(\bar{P}_{gen}, \tilde{P}^{s}_{wind}, \tilde{P}d) \tag{5.16}$$

where:

$$R(\bar{P}_{gen}, \tilde{P}^{s}_{wind}, \tilde{P}d) = \sum_{t \in T} \Big(I_{\cos t}(\bar{P}_{gen}(t), \tilde{P}^{s}_{wind}(t), \tilde{P}d(t) \Big) - F_{\min} \tag{5.17}$$

$$I_{\cos t}(\bar{P}_{gen}(t), \tilde{P}^{s}_{wind}(t), \tilde{P}d(t)) = P_{loss}(t) \times \lambda_{mkt} \tag{5.18}$$

$$P_{loss}(t) = \tilde{P}d(t) - \tilde{P}^{s}_{wind}(t) - (s(t) \times \bar{P}_{gen}(t)) \tag{5.19}$$

5.2.2.1.1 Power demand uncertainty

As shown in the Eq. 5.20, the market demand $\tilde{P}d(t)$ is the deterministic variable representing the market demand uncertainty.

$$Pd_{\min} \le \tilde{P}d(t) \le Pd_{\max} \tag{5.20}$$

where $Pd_{\min}$ and $Pd_{\max}$ are the minimum and maximum demand limits across the market respectively.

5.2.2.1.2 Wind power constraints

In the Eq 5.21, $\tilde{P}^{s}_{wind}$ represents the uncertainty in the wind system across each scenario, where $Pw_{mkt}(t)$ and $Pp(t)$ is the wind power used for meeting the market demand and the PSP in pumping mode at t^{th} time respectively.

$$\tilde{P}^{s}_{wind}(t) \geq Pw_{mkt}(t) - Pp(t) \times (1 - s(t)) \tag{5.21}$$

5.2.2.2 Optimality condition of min-max approach

Optimal condition of the min-max approach has been derived from the main theorem of game theory with convex function and given in the Eq. 5.22. Two feasible scenarios: worst-case scenario $\left(P^{-}_{wind}, Pd^{-}\right)$, at which system uncertainty risk is at its maximum value and 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 shown in Eq. 5.22.

$$R(\hat{\mathrm{P}}_{\mathrm{gen}}, P^{-}_{wind}, Pd^{-}) = R(\hat{\mathrm{P}}_{\mathrm{gen}}, P^{+}_{wind}, Pd^{+}) \tag{5.22}$$

where, $\hat{\mathrm{P}}_{\mathrm{gen}}(\mathrm{t})$ is the optimal value for the min-max approach and satisfying the optimality condition of min-max approach.

5.3 METHODOLOGY

Min-max model as described in section 5.2.2 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 information of wind data and market demand. The methodology to solve the min-max problem is described 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 3.2 and 5.2 respectively.

ii. Optimized the deterministic optimal scheduling of wind-PSP using the planned value of wind and market demand as given in section 5.1 and calculated the minimum imbalance $F_{\min}$ using the model as given in section 5.2.1.

iii. Calculated Risk for the nominal $R(\hat{\mathrm{P}}_{\mathrm{gen}}, P_{wind}^{+}, Pd^{+})$ and worst-case $R(\hat{\mathrm{P}}_{\mathrm{gen}}, P_{wind}^{-}, Pd^{-})$ scenarios as determined in the section 5.2.2.2.

iv. Optimized the min-max value while satisfying the optimality condition as given in Eq. (5.22)

v. If the risk for both nominal and worst-case are equal then the planned value of $\hat{P}_{gen}$ is found for the wind-PSP system

5.4 RESULTS AND DISCUSSIONS

In the min max approach, the wind power output has been forecasted for six different scenarios. 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 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.

The combined operation of the wind-PSP system has been shown in Fig 5.2, whereas the generation and pumping operation of PSP for the both cases (Case-I and Case-II) is shown as Fig. 5.3. From Fig. 5.2-5.3, it has been found that PSP units were efficiently scheduled to reduce the market imbalance. For variable speed operation of PSP, Case-II is seen to be more successful to reduce the market imbalances as compared to Case-I (Fig 5.2).

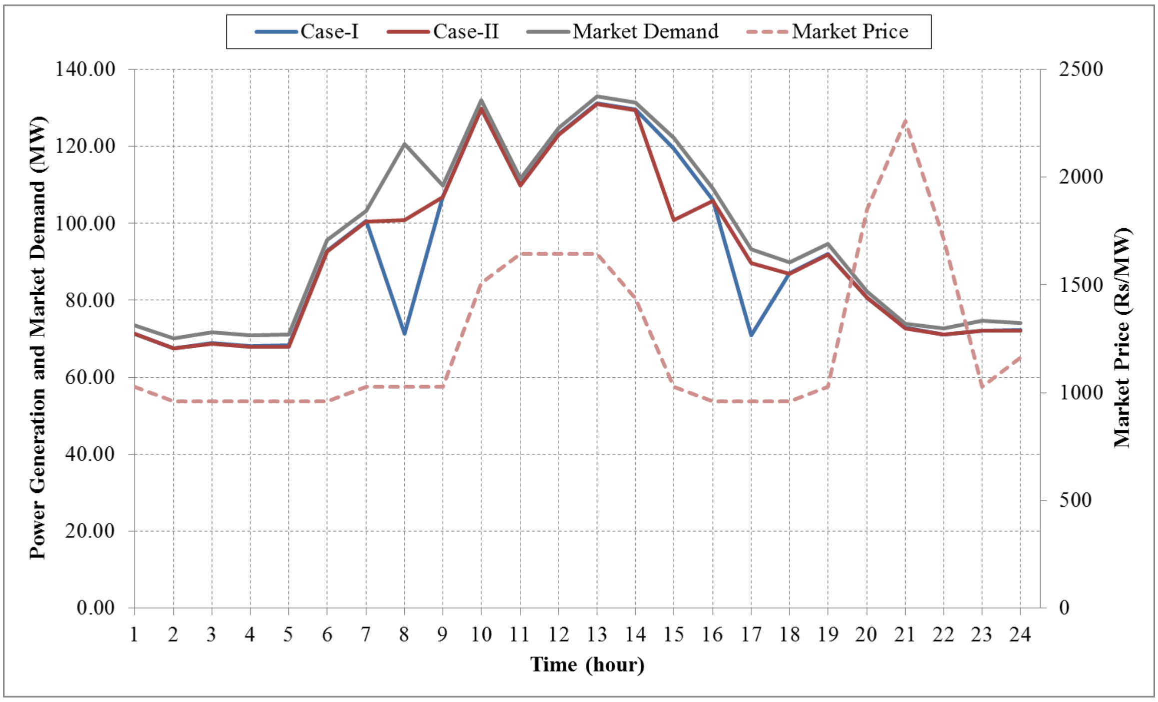


Fig. 5.2 Combined Wind-PSP Operation

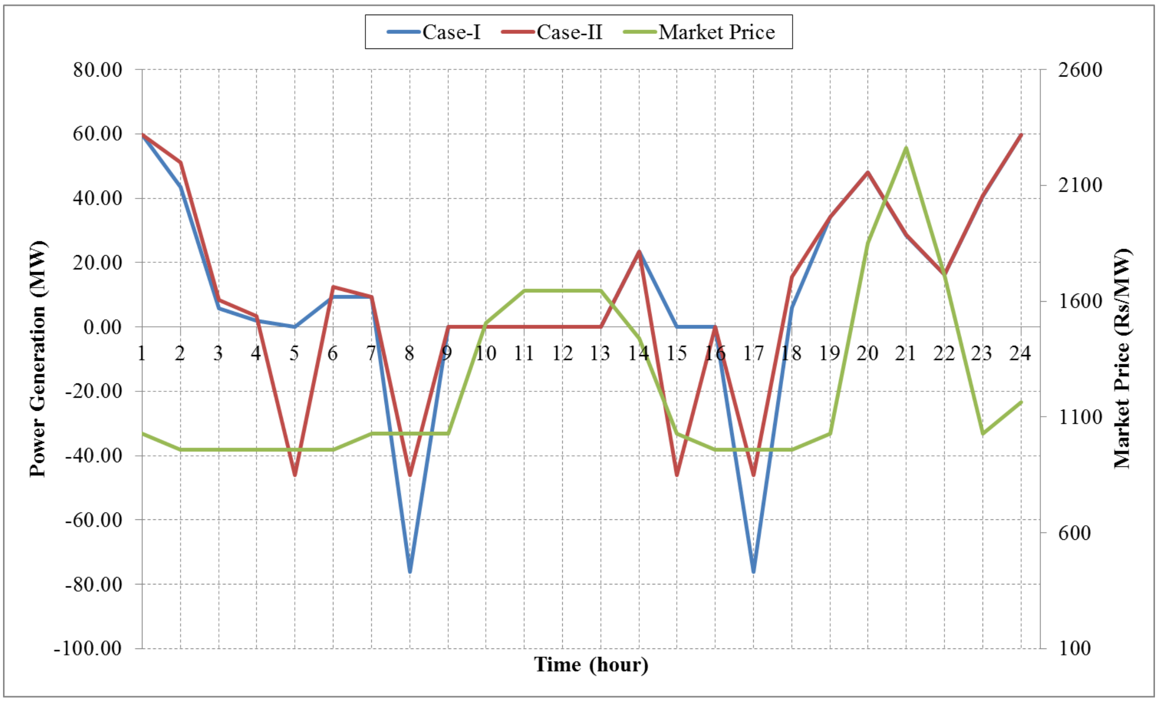


Fig. 5.3 Pumped Storage Plant Operation

Both wind and PSP supply the power to the market at the given market price. Fig. 5.3, show that during the low market price e.g. during hours 8 and 17 in Case-I and during hours 5, 8, 15 and 17 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 energy price, it operates in generating mode and uses stored energy from the upper reservoir. Table 5.1 represents the risk across the Wind-PSP system for the selected two scenarios (Nominal and Worst-case). From Table 5.1, it is seen that the use of variable pumping operation for Case-II can decrease the risk by 20 % for wind-PSP system by decreasing the imbalance costs as compared to Case-I, where the results for the nominal and worst case scenario would remain same for both the cases.

Table 5.1 Risk across Wind-PSP system (*Rs*)

Cases	Scenario	
	Normal	**Worst-Case**
I	131408.1	131408.1
II	105633.8	105633.8

From the Fig. 5.2 and 5.3, 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 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 as a significant tool in decision-making process and can adapt more to the existing practical systems by addressing the limitations mentioned above.

CONCLUSIONS AND RECOMMENDATIONS

Due to competitive nature of the deregulated market, it is difficult for wind energy generation to compete with conventional energy generation without use of energy storage system being intermittent and variable in nature with uncertainties. To compete in the market as well as to reduce the uncertainty, utilities integrate intermittent renewable energy sources such as wind and solar with energy storage devices like flywheel, battery, compressed air storage and pumped storage plants etc. For the large size wind energy farms, PSP a mature technology, is economically viable energy storage option. The objective of the present study is to increase the overall profit across the wind-PSP system for day-ahead market by developing wind-PSP model scheduled to store the unutilized wind energy effectively and efficiently. Significant improvements have been achieved in scheduling techniques for the accomplishment of the market demand and reducing the market uncertainty.

6.1 CONCLUSIONS

The following conclusions are drawn from the present study:

i. In view of concern for climate change, rising fossil fuels prices and favorable policy, wind energy development is growing rapidly globally. Due to its intermittent nature, its integration with large size PSP is necessary for large scale penetration

ii. The wind and pumped storage scheduling problem is formulated as a mixed integer nonlinear programming problem. The scheduling of PSP units was carried out by operating units at fixed speed during the pumping mode, which reduced the market imbalance by 60% as well as increased the overall profit to 19%. The profit of this approach has been further improved to 31%, by replacing the fixed pumped storage unit with a variable speed pumping unit.

iii. Wind energy has been forecasted for day-ahead power market. The imbalance in forecasted energy and market demand has been reduced by controlling the variable speed of pumped storage plant in both generating and pumping modes. By operating the pump unit in varying speed mode, it not only increased the total revenue but also decreased the market imbalance by 38% which otherwise would have caused the revenue loss during the combined operation.

iv. Uncertainty in the wind data always effects the scheduling operation of wind-PSP system, which has been analyzed by using a stochastic approach. Probabilistic forecasting technique has been used to forecast the uncertainty in wind data for day-ahead market. It has been found that PSP units stored the power especially during the periods having low market price and excess wind generation thereafter utilized this power to reduce the power imbalance between the wind generation and market demand.

v. For the grid connected wind-PSP system, whenever the wind energy is inadequate for the pumping operation of PSP, the remaining power is drawn from the grid. From the study, it is concluded that the utilization of wind energy has increased by 1 to 4% by operating with grid system under uncertain condition improving the overall profit by 4%.

vi. The adjustable speed type PSP unit increased the revenue across the wind-PSP system for the each level of uncertainty as compared to the conventional fixed speed unit of PSP.

vii. Knowledge of the maximum available risk under uncertain condition of wind is always required for providing the stable operation of wind-PSP system. Therefore, a Taguchi method based model has been developed to optimize the wind-PSP operation under uncertain condition. Under this method, the various levels of risk evaluated across the system by partial set of experiments and offered a simple and systematic approach. This orthogonal array method used less number of experiments to save the computation time and reduced the operation risk by 64% for wind-PSP system under wind data uncertainty. The major advantage of this approach is to design a wind-PSP system, which is able to withstand any level of risk and provided the stable performance under uncertain condition.

viii. 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 would remain same for all the scenarios considered. By using this method risk was reduced by 20% for operating variable speed unit as compared to fixed speed PSP unit.

ix. The developed min-max optimization model has limitations in decision making and requires consideration of constraints such as balance between initial as well as final levels of the upper reservoir for a PSP plant to make the developed model more practical.

x. The developed wind-PSP models can be considered as significant tools in decision-making process and can be adapted to the existing practical systems with little modification.

6.2 RECOMMENDATIONS

Following are the some recommendations made from the present work:

i. In spite of wind energy being an intermittent and variable source, scheduling of wind energy system with PSP is recommended as it helps in increasing the profit under day-ahead market and meet the peak demand.

ii. A new approach based on Taguchi technique is recommended to manage the risk for the stable operation of wind-PSP system.

iii. The presented scheduling model can be considered by the power producers, load dispatch center, traders, utility and regulators as a significant tool in decision-making process which is easily adaptable for existing practical systems.

6.3 FUTURE SCOPE

Sequel to present study, following research work may be explored further in future:

i. To plan the optimal size of Wind and PSP units, the unit size optimization techniques may be developed for improving the operational efficiency of the system.

ii. In the present study, the ancillary service covering the energy imbalance has been addressed by PSP. Other ancillary services such as (1) regulation and frequency response; (2) reactive supply and voltage control; (3) scheduling, system control and dispatch service; (4) spinning; and (5) non-spinning operating reserves available from PSP may be studied in future using presented model.

iii. The modeling of wind-PSP system has been studied here without considering the integration of other generating sources. For the feasibility and benefits of this model, the presented model may be further expanded by using other sources of energy such as solar, hydro, biomass and nuclear etc.

iv. Classical MINLP technique has been used to implement the game theory based approach for min-max optimization. However, this approach is unable to handle the complex system with large number of constraints. Thus, it is recommended to explore the use of evolutionary techniques like GA, PSO to implement the game theory based approach considering the different constraints.

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LIST OF PUBLICATIONS

A. In International / National Journals

1. Javed Dhillon, Arun Kumar and S.K. Singal, "Operation of Wind and Pumped Storage plant under Deregulated Environment", Water and Energy International Journal, 69(11), pp. 30-34, 2012.
2. Javed Dhillon, Arun Kumar and S.K. Singal, "Optimization methods applied for Wind-PSP operation and scheduling under deregulated deregulated market: A review", Renewable and Sustainable Energy Reviews, 30(1), pp. 682-700, 2014.
3. Javed Dhillon, Arun Kumar and S.K. Singal, "Stochastic approach for providing the operation of Wind and pumped storage under Deregulated Environment", International journal of Green Energy. (**DOI:**10.1080/15435075.2014.909358)

B. In International / National Conferences

1. Javed Dhillon, Arun Kumar and S.K. Singal, "Short Term Wind-PSP Scheduling Using MINLP Approach" , 6th international Multi Conference on Intelligent Systems, New and Renewable Energy Technology and Nanotechnology (IISN,2012), Klawad, Yamunanagar, India, pp. 71-75, March 16-18 , 2012.
2. Javed Dhillon, Arun Kumar and S.K. Singal, "Scheduling of Wind and Pumped Storage Plant under Day ahead market", 17th International Seminar on Hydropower Plants, Vienna university of Technology, Vienna, Austria, pp. 53-62, November 21-23, 2012.
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