TECHNO-ECONOMIC STUDY OF AN EXISITNG PUMPED STORAGE PLANT

Ph.D. THESIS

by

N. SIVAKUMAR

DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

MAY, 2014

TECHNO-ECONOMIC STUDY OF AN EXISITNG PUMPED STORAGE PLANT

A THESIS

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

DOCTOR OF PHILOSOPHY

in

WATER RESOURCES DEVELOPMENT

by

N. SIVAKUMAR

DEPARTMENT OF WATER RESOURCES DEVELOPMENT & MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

MAY, 2014

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"TECHNO – ECONOMIC STUDY OF AN EXISTING PUMPED STORAGE PLANT"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Water Resources Development and Management of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during the period from August, 2008 to May, 2014 under the supervision of Prof. Devadutta Das, Emeritus Fellow, Department of Water Resources Development and Management and Prof. Narayana Prasad Padhy, Professor, Electrical Engineering Department, 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.

(N. SIVAKUMAR)

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

(Narayana Prasad Padhy)
Supervisor

(Devadutta Das)
Supervisor

Date:

The Ph.D. Viva-Voce examination of **Mr. N. Sivakumar,** Research Scholar, has been held on…………………………….

Signature of Supervisor (s) | Chairman, SRC | External Examiner

Head of the Department/Chairman, ODC

ABSTRACT

The growing economy with corresponding increase in power demand causes more challenges in power sector of developing countries. In India, the increase in peak power demand necessitates energy storage schemes over and above the storage - hydro, oil and gas based peak power plants to ensure power system stability. In utility energy storage schemes, the Pumped-hydro energy storage schemes (PHES) attract more attention even in the developed countries due to their unique operational flexibility over other energy storage systems. In India, PHES are developed for improving the net efficiency of the base load thermal power plants. The availability of suitable topographies, hydro-thermal ratio imbalance in various regions, optimal storage capacity for flexible power system operation, requirement of spinning reserve, increased generation from renewable energy sources gives a thought for the planers and executors to implement these schemes to meet peak demand.

Under these circumstances, this research initially addresses the present operating conditions of the existing PHES of the country, their operational constraints, historical performance and future prospects. In the beginning, these schemes were operated only at times of peak and major power plant outages due to less cycle efficiency. The analysis of the existing schemes reveal that the major reason for less output from the PHES in India than that envisaged in the planning stage is deficit off-peak power available for pumping almost in all the regional power grids except the north-eastern grid. But gradual increase in efficiency has been realized from PHES operation after the introduction of the availability based tariff (ABT) in 2003.

Further, a performance evaluation has been carried out for the 26 year-old Kadamparai pumped storage plant (4x100 MW) located in the state of Tamil Nadu, India since it is the first successful pumped storage plant of the country by operation. Detailed analysis of the plant have been mainly focused on i) reservoir regulation, ii) introduction of variable speed technology of pumped storage and iii) the economic aspects of pumped storage plant.

Reservoirs are the major part of a hydro power plant especially for a pumped storage plant since recycling process of water is essential. Hence the reservoir regulation of the Kadamparai pumped storage plant has been analyzed. For this purpose, a water regulation model has been developed based on hydrological mass balance with the

objectives of energy maximization and spill minimization. Monthly reservoir storage curve and operating policies have also been derived and presented for future operation of the plant efficiently.

Variable speed operation is a new area of study in pumped storage operation. The newly planned pumped storage schemes are mostly equipped with this technology worldwide. But, in India no such schemes are existing now and the first variable speed pumped storage scheme of the country (Tehri) is under construction. Hence a variable speed analysis has been conducted to check the feasibility of variable speed drives installation in the Kadamparai pumped storage plant during renovation and modernization due in next few years. The efficiency difference between fixed and variable speed operation has been analyzed and the results have been presented. Further, the efficiencies and the discharges derived from the efficiencies have been analyzed with existing five years (2006-2010) reservoir data and the pumping benefits have also been worked out to determine the additional energy likely to be generated. The analysis reveals that the results are encouraging and hence variable speed machines have been recommended for the plant during renovation and modernization.

In addition with the above technological analysis, an economic analysis has also been carried out in this research. Preliminarily, various costs involved in pumped storage operation of the country have been analyzed which will be useful for the planners and policy makers for future planning of pumped storage schemes. Regarding Kadamparai, an economic analysis has been carried out with pumping energy cost to check the economic status of the plant in the state grid. The analysis reveals that the considerable economic benefits obtained by the PHES in the state grid after 2003 i.e. after the introduction of ABT and the cost of generation from the pumped storage plant is comparatively less than that of other peaking plants such as gas and diesel peaking power plants of the state.

The research reveals that the installation of pumped storage plants is essential for the flexible operation of Indian power system and to optimally utilize the vast renewable energy sources of the country. Regarding Kadamparai analysis, the derived reservoir storage curves, operating guidelines and the variable speed analysis are certainly helpful to increase the plant performance.

ACKNOWLEDGEMENT

It gives me immense pleasure to express extreme veneration and profound sense of gratitude to my supervisors – Prof. Devadutta Das, Emeritus Fellow, Department of Water Resources Development and Management, Prof. N. P. Padhy, Professor, Electrical Engineering Department, Indian Institute of Technology Roorkee, Roorkee for their invaluable guidance, inspiring support, constant encouragement, abundant counsel and constructive criticism during the entire course of this research work which made this work possible.

My sincere thanks to Prof. Deepak Khare, Head, WRD&M, the DRC committee members: Prof. Nayan Sharma, Prof. M. L. Kansal and Dr. Vinay Pant for their constructive comments on my presentations.

I am extremely thankful to former Chairman Shri C. P. Singh, IAS and Chief Engineer (Hydro), Tamil Nadu Electricity Board for permitting to visit Kadamparai pumped storage plant and providing all the necessary official and technical support.

I intend to record my gratitude to Er. N. S. Namasivayam, Executive Engineer and Er. R. Ragothaman, Former Executive Engineer, Kadamparai pumped storage plant for their continuous support during this period in providing plant data and sharing their operational experience. I am also thankful to Er. V.R. Geethananthan, Chief Engineer, Er. V. Mekala, AEE, Er. V. Sundar, AEE, TNEB for their support during this research.

I am very much indebted to Dr. A. R. Senthil Kumar, Scientist, National Institute of Hydrology, Roorkee for his continuous support throughout the period of the thesis and his valuable guidance related to hydrological analysis.

I am very much obliged to Prof. R. Krishnamurthi, Prof. R. Jayaganthan, and my senior Dr. Niranjan Kumar and their families to make my stay pleasant at Roorkee, their caring and support thorough out this period.

I am thankful to Dr. K.K. Mahanta, Shri Azeem Gupta, Shri Umesh Gautam for their support during this period.

I acknowledge all the teaching and non-teaching faculties of WRD&M for their support and making my stay pleasant during this period.

I express my sincere thanks to MHRD, India for providing me financial support.

The blessings of my grandparents Karnam M.C. Govindhasamy Padayachi, Shrimati Dhanabakyam, Shri K. Kandhasamy Padayachi, Shrimati Veerammal and my uncle Pulavar R. Thamizh Vendhan, who are no more, enabled me to succeed in my academic endeavors.

I wish to express deep sense of gratitue to my parents Shri G. Natarajan, Shrimati K. Pavunammal who brought me to this beautiful world and for their support. I am also grateful to my brother Shri N. Senthil Kumar for his support.

I would like to thank my uncle and aunty Shri P. D. Muthusamy and Shrimati G. Inbavalli, who shaped my whole academic career and their caring throughout my life.

I would also like to thank my uncle Shri S. Kasinathan for inspiring me in research and his continuous support.

I am particularly very much thankful to my friend Shri R. Gowri Shankar for his personal and technical support during the course of this research work.

I acknowledge the support of my fellow friends Shri Danie Roy, Shri Gosavi Vaibhav Eknath, Shri Prabhu, Shri Prince, Shri Naman Sharma, Shri Siva Chidambaram, Shri Sakthivel and Nandh Kishore.

At last, I express my sincere thanks to all my teachers from schooling to IIT Roorkee, friends and relatives, who have helped me directly or indirectly during the course of this research work.

(N. Sivakumar)

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$S1_t$	Storage of the upper reservoir at time *t*
$S1_{t+1}$	Storage of the upper reservoir at time *t+1*
$S2_t$	Storage of the lower reservoir at time *t*
$S2_{t+1}$	Storage of the lower reservoir at time *t+1*
$IL1_t$	Local inflow from the catchment of upper reservoir at time *t*
$IL2_t$	Local inflow from the catchment of lower reservoir at time *t*
$Q1_t$	Discharge from the upper reservoir for power generation at *t*
$Q2_t$	Discharge from the lower reservoir for power generation at *t*
$SP1_t$	Spill from upper reservoir at time *t*
$SP2_t$	Spill from lower reservoir at time *t*
IP_t	Pump inflow from lower reservoir at time *t*
$S1_{min}$	Minimum storage of upper reservoir
$S1_{max}$	Maximum storage of upper reservoir
$S2_{min}$	Minimum storage of lower reservoir
$S2_{max}$	Maximum storage of lower reservoir
IP_t	Maximum pump inflow from lower reservoir for t
P_{in}	Power input to the turbine
ρ	Density of water
g	Acceleration due to gravity
Q	Discharge
Φ_n	Peripheral velocity factor
n	Rotational speed
D	Diameter of the turbine runner
H	Net head
f	Rated frequency
P	Number of machine poles
η_M	Motor efficiency
η_P	Pump efficiency
C	Annual net benefit
Gen	Net generation
Cost1	Cost of power generation

Cost2	Cost of pumping energy
Pump	Net pump consumption
AFC	Annual fixed cost

LIST OF ANNEXURES

LIST OF ABBREVIATIONS

ABT	Availability Based Tariff
AFC	Annual Fixed Cost
ANN	Artificial Neural Networks
BHEL	Bharat Heavy Electricals Limited
CAES	Compressed Air Energy Storage
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
DASM	Doubly-fed Asynchronous Machine
DC	Direct Current
DE	Design Energy
DFAM	Doubly Fed wound rotor Asynchronous Machines
DFIG	Doubly Fed Induction Generator
DPR	Detailed Project Report
DVC	Damodar Valley Corporation
FRL	Full Reservoir Level
GA	Genetic Algorithm
GDP	Gross Domestic Product
GEC	General Electric Company
GTO	Gate Turn-off Thyrister
IPP	Independent Power Producer
IS	Indian Standards
KPH	Kadamparai Power House
LBPH	Left Bank Power House
LMP	Locational Marginal Price
Mcft	Million Cubic Feet
MCP	Market Clearing Price
MDDL	Minimum Draw Down Level
MMGA	Multi-objective Genetic Algorithm
MU	Million Units
O & M	Operation and Maintenance
PAT	Pump As Turbine
PHES	Pumped Hydro Energy-storage Schemes

PSP	Pumped Storage Plant
PSS	Pumped Storage Scheme (s)
PWD	Public Works Department
RBPH	Right Bank Power House
RES	Renewable Energy Sources
SDP	Stochastic Dynamic Programming
SFC	Static Frequency Converter
SHP	Small Hydro Power Plant
TANGEDCO	Tamil Nadu Generation and Distribution Corporation Limited
TMC	Thousand Million Cubic Feet
TNEB	Tamil Nadu Electricity Board
UA	Upper Aliyar
UAPH	Upper Aliyar Power House

Chapter 1
INTRODUCTION

1.1. OVERVIEW

India is the eighth largest economy in the world by nominal GDP (Gross Domestic Product), third largest economy by PPP (Purchasing Power Parity) as per World Bank report with five years GDP of 8.7% and the 5th largest energy consumer [30]. The total installed capacity of the country as on 31-03-2014 as per CEA (Central Electricity Authority) is 243,028.95 MW which comprises of 168254.99 MW thermal (69%), 4780 MW nuclear (2%), 40531.41 MW hydro (17%) and 29462.55 MW from renewable energy sources (12%). It is great challenge to meet out the supply-demand gap in India due to growing economy and scarcity of power. Energy availability of the country as on March, 2014 is 959,614 MU against the requirement of 1,002,045 MU with shortage of 4.2%. Similarly the peak power met by the country is 129,815 MW against the requirement of 135,918 MW with shortage of 4.5%. The identified hydro potential of the country is about 84,000 MW at 60% load factor (about 1, 50,000 MW installed capacity) [43]. In addition, 6780 MW installed capacity from small, mini, and micro hydel schemes have been assessed. Also, 56 sites for pumped storage schemes with an aggregate installed capacity of 94,000 MW have been identified for the future development [44]. The country so far utilizes about 20% of hydro and 5% of pumped storage of the identified capacity.

Pumped hydropower systems have been used for bulk energy storage all over world since many decades. As on 2009, it accounts for more than 99% of bulk storage capacity, around 127 GW [109]. Bulk pumped storage systems are used to meet peak demand, absorb surplus power during off peak periods especially from thermal and nuclear power stations and used as emergency reserve during thermal/nuclear unit outage contingencies. Consequent to the oil crisis faced in 1970s, many countries started adding pumped storage schemes in their power systems. Pumped storage plants were developed along with thermal and nuclear stations throughout the world so that these plants more or less operated at constant load. India also felt the need of energy storage in their power system considering the prime benefit of using surplus power to pump water during off peak period and to meet peak demand exclusively during summer months from pumped storage schemes.

During 1965 – 70, the power system in India grew in capacity to cater to the ever increasing industrial and agricultural load demands to in step with increasing gross domestic product (GDP). To cater to the increase in load demand in short span to close the gap between demand and supply, more number of thermal power stations and nuclear stations were planned during the 1970s. Hence, first pumped storage of mixed type was added to the grid in 1982 with a capacity of 705.6 MW (Nagarjunasagar, Andhra Pradesh). During the period from 1982 to 2007, nine (9) mixed type pumped storage schemes with a total installed capacity of 3654 MW were commissioned in the country. The mixed type pumped storage hydroelectric facilities developed in India have been planned considering the necessity of such plants influencing decision regarding the output on one hand and taking into cognizance the irrigation requirements on the other. Another two (2) pure pumped storage schemes have been added to Indian grid during the period 2008-2009 i.e. Purulia (West Bengal) and Ghatghar (Maharashtra). The list of pumped storage plants of the country and their operational status on pumping mode is shown in Table. 1.1.

Table 1.1 List of Pumped storage schemes in India

Name of the project	State	Capacity (MW)	Pumping mode operation
Nagarjunasagar	Andhra Pradesh	705.6	Not yet
Paithan	Maharashtra	12	Working
Kadamparai	Tamil Nadu	400	Working
Kadana	Gujarat	240	Not yet
Panchet Hill	DVC	40	Not yet
Ujjain	Maharashtra	12	Working
Bhira	Maharashtra	150	Not yet
Srisailam	Andhra Pradesh	900	Working
Sardar Sarovar	Gujarat	1200	Not yet
Purulia	West Bengal	900	Working
Ghatghar	Maharashtra	250	Working

The existing and present operating performances of the above plants are stated in detail in Chapter - 2.

The use of energy storage devices has not expanded significantly in India as compared with countries like Japan and China. More reserve generation capacity is available in developed nations where as India possesses less reserve capacity in their power system. Hence, operating pumped storage schemes towards profit maximization in a market driven scenario as adopted in developed countries, does not suit to the Indian context since the country is facing persisting peak and energy shortage in spite of developments made so for. Sustainable development of pumped storage plant depends on country's energy policy planning. However, it is more important to know how its practical application and benefits would suit to the country's needs.

The Indian Power Sector is facing major challenges today with the introduction of reforms, globalization and liberalization policy of the government. The installed capacity of power system has crossed 243GW as on 2014, along with transmission expansion and the target is 300 GW by 2022. In India, the demand is found always exceeding the supply and poses problem on stability and security of power system.

The present research reported herein, reveals how the pumped energy storage schemes have been developed in Indian context during the past thirty years and how they are going to be utilized more in pumping operation so as to increase the station output optimally. It considers more regulations followed on frequency as the operational frequency is gradually moving towards 50 Hz. The thesis presents an overview of the country's power development status, information about India's pumped hydro-power potential development made from 6^{th} five year plan up to 11^{th} plan period (1980-2012), its current status of utilization, schemes under construction, and the plan for development over the next 10 year period and beyond, due to addition of wind and solar system in the power system. The role of pumped hydro-power plants operation within the overall power sector, the economic analysis of existing major pumped storage schemes, and the issues and barriers that are being faced in developing and operating the pumped hydro-power schemes have been also discussed.

Further, a detailed analysis has been carried out to evaluate the performance of Kadamparai pumped storage scheme, which has been operational since 1987 on both the modes – pumping and generating. The historical performance of the plant has been studied and analyzed and remedial measures have been suggested to improve the plant performance. Three analyses have been carried out to study and improve the performance of the plant. In the first analysis, the plant's reservoir operation has been studied and a reservoir regulation has been framed to improve the existing operation with the help of a simulation model. The operating guidelines have also been framed to maximize the performance and minimizing the spill to operate the plant efficiently as suggested by Central Electricity Regulatory Commission (CERC), Government of India guidelines since the plant doesn't have such standard operating procedure at present. Variable speed operation is the latest technology in pumped storage development worldwide. Replacing variable speed drives with existing fixed speed drives have been suggested while carrying renovation and modernization since the plant has crossed 26 years of operation. For this purpose, a detailed analysis has been presented with five year daily head variation data to ascertain the benefits of variable speed operation over conventional fixed speed operation. The economical operation of pumped storage scheme is another important factor ought to be taken in to account for the analysis. Hence, the economic analysis has also been carried out for the plant to check whether a pumped storage scheme can sustain in the Indian context economically.

1.2. PUMPED STORAGE SCHEMES

1.2.1. History

The history of the pumped storage plant can be traced back to the commissioning of 70 KW capacity in Zurich, Switzerland in 1882 [25]. A major plant with a capacity of 1500 KW was built in Schlaffhausen, Switzerland in the year 1909 and it was considered to be a significant development in the pumped storage system. This was equipped with separate pump-turbine arrangement. Further, many pumped storage schemes are developed mostly in European countries such as Germany, Switzerland, and Italy in initial stages [19]. The development of pumped storage schemes in USA was slow as compared to the development in European countries. The development of pumped storage schemes started in Japan after installation of many nuclear plants. By 1933, reversible pump turbines were widely available and the same were used in the installation of pumped storage schemes. The construction of pumped hydro schemes was in full swing during 1960 to 1980. At present, the pumped hydropower plant at Bath County, United States is the world's largest plant with an installed capacity of 2710MW [87].

1.2.2. System

By construction, it is a conventional hydro power plant with the option of pumping. It consists of two reservoirs, one is located at a low level called 'lower reservoir' and the other at a higher elevation called 'upper reservoir'. During off-peak hours of the grid, the water is pumped from the lower to the upper reservoir where it is stored. During peak hours, the water is released to the lower reservoir, passing through hydraulic turbines, for generating electrical power. Both the reservoirs may be artificial or natural based on the topology. If any natural stream flow persists, it may enable additional generation. Such schemes are called mixed pumped storage schemes and the schemes without natural inflow are called pure pumped storage schemes.

1.2.3. Operation

Pumped storage plants are designed to operate on a daily, weekly, monthly or seasonal cycle. However, most of the stations in the world are operated on daily cycle where the storage required is available by pumping and used for generation.

1.2.4. Benefits

The major advantages of pumped storage schemes are quick start to meet load demand during peak hours and excellent load following characteristics. It has significant impact on the system load curve for leveling the peaks and valleys. Commissioning of these schemes in a power system can increase the grid stability and reduce the load shedding by generating energy during peak hours. The efficiency of the thermal power plants can be improved by combined operation of pumped storage schemes when demand is below certain level. In such periods, the pumped storage station can pump the water back and act as a load of thermal plants, which can stabilize the system. The notable characteristic of pumped storage scheme is its quick response to sudden load changes in a grid, while the thermal plants have very slow response. Hence PSP can be used as frequency regulators of the grid as well as spinning reserve [101].

1.2.5. Machine design

During initial developmental phase, separate pumps and turbines were used. But such plants were of low capacity. In this recycling process, all the hydraulic, mechanical and electrical losses are accounted for and the overall cycle efficiency approximately to 66% - 78% [101]. As an efficiency improvement measure, use of separate hydraulic machines with switching valves for pump and turbine modes was subsequently used. But this arrangement increased the cost of the hydro-mechanical equipment and of the powerhouse. The traditional reversible pump-turbines are designed and the turbine efficiency of reversible pump-turbine is less since priority is given for increased pump efficiency during design. Later, multistage pump turbines are built for higher head operation. Better results are obtained with two-speed synchronous motor-generators. Recent pumped storage machines are designed with variable speed operation to get higher efficiency, better stability of operation and reduced damage from cavitation.

1.3. LITERATURE REVIEW

This research has been mainly carried out to address the pumped storage sector and its future in India. For this main objective, a case study i.e. Kadamparai pumped storage plant has been carried out to understand the techno economic status of a pumped storage plant in Indian context. Before entering into the detailed analysis of Indian pumped storage sector and the specific case study, a literature review has been carried out to understand the fundamental concepts of pumped storage schemes, operational strategies and various research works pursued in this area worldwide. The operation of pumped storage schemes worldwide has been published in several reputed international journals and conferences. The literatures reviewed for this study are the papers published in journals by IEEE, Elsevier and ASCE, etc. However, the publications related to the current research problem are discussed under the following categories.

1.3.1. Energy storage

Bridging supply-demand gap is a challenging task in a power system. Conventional generating plants such as nuclear and coal based plants cannot adjust their output to address the continuously varying load demand. Further, the stochastic nature of non-conventional energy resources like wind and solar, makes the power schedule more complex. To manage such unexpected load variations, power system generally needs about 8-10 % of the reserve in addition to the installed capacity online [82]. Energy storage schemes have been used as reserve and peak load plants in a power system since many decades. The role and characteristics of various energy storage schemes in a power system have been explained in many articles including [8], [13], [40], [45], [53], [70].

Storage schemes are essential in a power system for load leveling, fluctuation smoothing, uninterruptible power supply and as an emergency power source. Kondoh et al. (2000) surveyed and compared the various characteristics such as capital cost, lifetime, output power densities, storage energy densities and losses in operation for the promising energy storages of pumped hydro, compressed air, secondary batteries, superconducting magnet, flywheels and capacitors. The authors concluded that each energy storage system has a suitable range of applications [58].

The energy storage technologies are broadly classified into two categories based on the duration of operation: small scale storage i.e. storage batteries, fly wheels, etc. and large scale storage systems i.e. Pumped Hydro Energy Storage Schemes and Compressed

Air Energy Storage (CAES). The fluctuations of small durations i.e. few seconds to minutes can be met out by small scale devices. Normally, the capacity of small scale devices varies from KW to few MW. If the fluctuation or the supply gap exists several hours, then the role of large scale storage is important in a power system. Generally, these large storage systems are designed for multi-MW capacity.

Energy storage schemes are used for the applications of system regulation, spinning reserve, peak shaving, load leveling and renewable energy applications in a conventional power system network. Dell and Rand (2001) have made an evaluation of major energy storage technologies for their application in centralized and distributed electricity supply systems. The authors indicated that energy storage schemes are essential where the power system consists of significant energy contribution from renewable energy sources as there are suitable to store large quantity of electricity from such sources [22].

A power system consisting of large thermal, nuclear and renewable energy sources like solar and wind needs energy storage schemes for sustainable operation. The stochastic nature of the renewable energy sources can be efficiently tapped by using the energy storage schemes. Robert B. Schainker (2004) presented an overview of different storage technologies for a sustainable power system operation especially for more renewable energy sources adopted power system [86]. Beandin et al. (2010) have also presented an up-to-date review of the state of technology, installations and some challenges of energy storage technologies especially for large scale renewable energy integration applications. The state of art reviews reveals that the storage plants will significantly improve the renewable energy utilization and economic use of the existing generation [9].

Regulation services are one of the major uses of energy storage schemes. Yang et al. (2008) demonstrated an evaluation process for the selection of energy storage schemes for regulation services [13]. The power system discussed by the author has large wind energy penetration. Several energy storage schemes have been compared with many selection criteria such like cost, life time, efficiency, etc. to overcome the problems from this large wind energy penetration

From the literatures, it is clear that the role of large scale energy storage in a power system is essential for any power system not only to meet the peaks, but also to meet the emergency situations and ensure the reliability of the system. So far, only two storage technologies considered as suitable technologies for large scale commercial operations are

Compressed Air Energy Storage and the Pumped Hydro Energy Storage. Only two successful installations of CAES worldwide are 110 MW capacity in United States and another 290 MW capacity in Germany [109]. The requirement of topology for the installation of these systems is specific, which limits the commissioning. PHES are cheaper compared to CAES, as water is the storage medium.

PHES are the only proven large scale (>100 MW) energy storage schemes for power system operation. Worldwide, there are more than 300 installations with total capacity of 127 GW [82], [109]. The increasing trend of installations and commercial operation of these schemes have been witnessed in recent years [21]. In addition, with the present capacity, it is expected that another 76 GW will be added by 2014 worldwide [82]. Many countries realized the feasibility of this technology and are planning for addition of pumped storage capacity to the power system, especially to facilitate the use of renewable energy sources.

1.3.2. Reservoir management

The efficient reservoir operation is not only required to meet consumptive use, but also to meet non consumptive use, for example hydropower generation. Many system models are available to arrive at the operation policies. Many general purpose models such as simulation models, optimization models and system analysis models based on network flow programming formulation have been developed as per the requirement of valley projects and applied to achieve higher performance of the projects [67], [107].

The university researchers and practitioners are very keen to apply optimization and stochastic analysis techniques related to reservoir management problems. Sule (1988) computed the reservoir water release policies for Shiroro dam hydroelectric power scheme in Northern Nigeria using a probabilistic dynamic programming model. Simulation results of the reservoir operating policies show that the efficient use of available resources could be achieved by operating the hydropower system between 8 and 12 hours per day using two or three units at a time [92]. Lund (1999) derived theoretical hydropower operation rules for the reservoirs in series, parallel, and single reservoir. The derived hydro power rules offer a simplified economic basis for allocating storage and energy in multi reservoir hydro power systems. The proposed approach was illustrated through theoretical examples [68]. Chen et al. (2007) developed an efficient macro-evolutionary multi objective genetic algorithm (MMGA) for optimizing the rule curves of a multipurpose reservoir system in

Taiwan. MMGA gives uniformly spread solutions for a two-objective problem involving water supply and hydropower generation. The results show that the proposed MMGA is highly competitive and provides a viable alternative to solve multi objective optimization problems for water resources planning and management [17]. Arunkumar and Jothiprakash (2012) have used non-linear programming model to optimize the operation of Koyna reservoir for maximizing the hydropower production subject to the condition of satisfying the irrigation demands [7].

Jha et al. (2008) adopted penalty factor incorporated energy maximization type objective function to reduce the spill from conventional hydro power plant of Japan. They used stochastic dynamic programming (SDP) models for obtaining the operating policy and identified storage guide curve for average year [50]. Chang (2008) proposed a real time flood control optimization model with linguistic description of requirements and exiting regulations for rational operating decisions. Genetic algorithm was used to search the optimal releases. He used proper penalty strategy to tackle problems of greater number of constraints and flood control requirements. He applied this strategy to Shihmen reservoir in North Taiwan and found that a penalty-type genetic algorithm could effectively provide rational hydrographs to reduce flood damage [16]. Shenglian et al. (2009) developed a new model based on combined guide curves for optimizing hydropower production and for better storage distribution among cascade reservoirs. They used particle swarm optimization algorithm for optimization and storage effectiveness index method for the storage allocation. The proposed model with the solution strategy is capable to produce an extra amount of electrical energy so as to save flood water resources annually [88]. Zahraie and Hosseini (2009) developed a genetic algorithm (GA) optimization model for reservoir operation optimization considering variations in water demands. The uncertainties in the demands are represented by different linear equations with different combinations of inflow and storage at the beginning of the month. Classic and Fuzzy regression analysis are used to find out the coefficients of the linear equations of operation policies. They evaluated the efficiency of operation policies based on the long term operation simulation of Zayandeh-Rud reservoir in central part of Iran. The performance indices indicated that the fuzzy linear regression equations based reservoir operation had the best long term performance in meeting variable demands [110].

The operating policies derived for conventional hydropower plants are based on the analyses performed by employing several optimization techniques reported in the literature as discussed above. But, the pure optimization process is a difficult one, in the operation of pumped storage especially in Indian context, since there are large numbers of constraints that limit operating flexibility. Many factors affect the day to day operation of pumped storage are Supply-demand-balance of a power system, Load profiles, Generation mix and Operation policy based on its cost of generation.

Few authors have investigated the use of various inflow processes and assumptions in energy maximization and in fixing the capacity of the plant or storage requirement for a pumped storage. However, no attempt was made to explore the possibility of reducing the spill in a mixed pumped storage in its lower reservoir based on its operating conditions and the storage capacity of the reservoir [36], [54].

1.3.3. Variable speed pumped storage schemes

Wilhelmi et al. described the potential advantages of variable speed operation in hydro power plants, possibilities of variable speed operation in Francis, propeller and Kaplan turbines, various topologies of variable speed operation, etc. to analyze the feasibility of variable speed operation. Further, the authors demonstrated an experimental setup with a small axial-flow propeller turbine which automatically controlled the converter circuit designed by using artificial neural networks (ANN). Based on the results, authors concluded that the variable speed technology is superior to the conventional fixed speed operation mainly from the efficiency point of view and few more considerations [106]. Fayolle and Lafon carried out a detailed analysis in which they discussed the evolution of the pumped storage schemes, various developments of the conventional machineries, variable speed technologies, the adverse effect of the power electronic converters, various starting methodologies, starting devices, various topologies, etc [19].

Schafer and Simond described the basic principles and advantages of variable speed machines for large scale hydro and pumped storage operations. The advantages of the variable speed machine installations in the grid has been demonstrated by simulating transient and steady - state operational behaviors by using SIMSEN software [84]. Koutnik et al. (2011) have also demonstrated a simulation model based on SIMSEN software for comparing the dynamic behavior of doubly fed induction generator with conventional fixed speed synchronous machine for Frades - II hydro power station unit of Portugal [51]. Simond et al. illustrated the expected benefits of adjustable speed pumped storage schemes in European grid by analyzing network performances and stability. Steady state and transient operation of a 230 MVA doubly-fed asynchronous machine (DASM) pumped storage unit was simulated by SIMSEN software for analyzing the benefits of variable speed operation [48].

Bocquel and Janming (2005) presented the setup and the characteristics of a 300 MW doubly-fed induction machine with cyclo-converter of Goldisthal pumped storage plant in Germany. The cyclo-converter of this plant is one of the largest of this kind in the world. The plant design, control strategies and the benefits of variable speed operation were detailed by the authors. The power station consists of two doubly-fed induction machines and two synchronous machines. In order to achieve the high grid stabilization for variable speed drives a new modified topology was proposed and simulated for various grid code requirements at various grid failures and also compared with other classical approaches [14]. Grotenburg et al. (2001) described the dynamic behavior of Goldisthal variable speed units with a simulation model of doubly fed induction machine. The simulation model considering the parameters of voltage, power, speed, network frequency and turbine controllers was developed for analyzing the dynamic behavior of the Goldisthal variable speed pumped storage scheme in the interconnected German power system [38].

A case study of Yagisawa pumped storage scheme which is the world’s first converter fed variable speed pumped storage power system is presented in [33]. Simulation of a one-line fault of the transmission line of the plant with EMTP (Electro Magnetic Transient Program) was demonstrated and the results were compared with the practical fault and protection system data. Kuwabara et al. (1996) presented a case study of 400MW Ohkawachi Power Station of Japan, which is the world's largest adjustable speed pumped storage unit. The design parameters, control systems of the machines were demonstrated in detail and the transient response characteristics with some real time performance tests were also presented [63].

Jen-Kuang et al. (2007) developed a mathematical simulation model of doubly fed adjustable induction machine for power system analysis. The proposed model employed with wire-wound AC excited rotor combined with field oriented control theory based exciter. The mathematical equations behind the model, control theories, principles and advantages of adjustable speed pumped storage operations were explained in detail. The simulation results of the model finally compared with the real time operation of 400MW

Ohkawachi power plant to ensure the appropriateness and found that it's suitable to analyze the dynamic characteristics of doubly fed induction machines [49].

Bendl et al. (1999) simulated the characteristics of a doubly fed induction generator for variable speed pumped storage application. The impact of active, reactive power changes and the mechanical speed to the system were demonstrated with a mathematical model. The higher harmonics due to the effect of the cyclo-converter were also analyzed [10]. Janning and Schwery demonstrated a doubly fed induction machine with a 3-level voltage source inverter for variable speed operation, compared the topology with cyclo-converters and listed the benefits of inverter solution [47].

Suul et al. (2008) demonstrated a topology for variable speed synchronous machine pumped storage hydropower plant with back-to-back voltage source converter to utilize the stochastic wind energy of the Faroe Islands isolated grid in efficient way. A simulation model was developed for analyzing the variable speed operation and control of the suggested topology. Results show that the variable speed pumped storage technology is very efficient for island grid operation to utilize intermittent wind energy with high stable frequency and reactive power management [96].

Inoue et al. (2010) demonstrated a renovation of existing pumped storage power plant from conventional fixed speed operation to adjustable speed operation. The renovation work was mainly planned for the frequency control at night. Authors detailed the layout of the proposed system, the restrictions such as existing equipment capacity, the maximum discharge and the space, etc. The operational range and benefits of adjustable system over fixed speed system were demonstrated [57].

The application and analysis of the performance of variable speed pumped storage scheme reported by the literatures indicate that the variable speed operation is the advanced technology in pumped storage operation and many PSS are being operated efficiently with this technology worldwide. But in India, all the pumped storage schemes are being operated with conventional fixed speed machines. The 1000 MW Tehri pumped storage scheme under construction, in India, will be first variable speed pumped storage schemes in the country.

The reservoirs having maximum to minimum head ratio of 1.25 is preferred for dual speed variable speed operation as a thumb rule. But, the economic and efficiency analysis of the particular site can only help to arrive at the final decision [19]. In India, experts have suggested to adopt variable speed machines for future pumped storage projects as it can improve the cycle efficiency of the plant for overcoming power shortages seen almost in all the regions.

1.3.4. Economics of pumped storage schemes

In conventional power system before deregulation, pumped storage schemes are considered as a part of thermal power plants. The thermal production cost of a power system can be minimized by proper scheduling of pumped storage plant within the system. Many conventional methods are used to plan the scheduling of pumped storage plant along with hydro power plants as elaborated in the literature [42], [65], [97], [98]. Scheduling of pumped storage plant is successfully solved by pseudo spot price algorithm reported by Fadil and Yasar (2000) [83]. In this analysis, the thermal power generation of a system and pumping and generating power limits are determined by the unit's active generation incremental costs and pseudo spot prices of purchased active power. The pumping and generating reservoir limits are also considered while evaluating the pseudo prices.

In the deregulated market environment, power suppliers, investors and traders are forced to operate their power plants towards profit maximization [89]. Revenue of a PHES, which is operating in deregulated environment, includes the energy sales during generation, and incentives from ancillary services fed to the grid. The pumping energy cost is added to the expenditure. It is possible to increase the revenue of a PHES in deregulated environment by optimizing the daily bids of day-ahead market. Kanakasabapathy and Swarup (2008) demonstrated an algorithm to maximize the profit of multi-unit pumped storage plant based on forecasted hourly market clearing price (MCP). The algorithm was tested with a pumped storage plant of New York [54].

An optimization method [24] for generation units in a power system for self-scheduling and trading with maximum profit and minimum risk in electricity market was developed. A test system consists of thermal, hydro and pumped storage units were considered in this study. The variances of market clearing prices were taken as risk constraint for self scheduling of generation units. The pumping and generation limits were determined based on MCP variations. An optimal bidding strategy was developed in [75] for individual pumped storage unit owners based on MCP variations.

In a deregulated electricity market, an energy storage scheme acts as a merchant unit and it has to earn most of its revenue from the sale of electricity to the market.

Connolly et al. (2011) in [18] investigated the economic viability of a PHES utilizing price arbitrage on various electricity markets. Three operational strategies were analyzed with various deregulated markets to maximize pumped storage scheme revenue by utilizing price arbitrages.

The operation of pumped storage plant depends on many uncertainties. A dynamic programming model developed to increase the gross margin of pumped storage plant, wherein the uncertainty in the market price and the inflow rate were integrated [46]. The study proved that the generation of pumped storage plant, when the locational marginal price (LMP) was high, produced high revenues than generating all the time. Similarly, the pumping of the plant when LMP was low reduced the pumping cost. This procedure generated more income to the pumped storage plant in the real power system.

1.3.5. Study on pumped storage schemes in India

Geetha et al. (2007) optimized the capacity of the pumped storage plant in Indian context under the ABT regime based on economic emission dispatch algorithm. The authors optimized storage and machine capacity for Kadamparai PHES in their case study [36]. Suresh et al. (2011) demonstrated an optimization model using heuristic algorithm for efficient use of pumped storage scheme in Maharashtra state of India. Daily load curve of the state was taken in the case study and cost optimization was worked out [94]. Verma et al. (2010) developed a model to investigate the combined operation of thermal, wind and pumped storage units for the profit maximization in varying wind, load, and price scenarios and the model was applied on IEEE-30 bus test system and satisfactory results were obtained [108].

A business model for Indian pumped storage schemes was demonstrated by Verma and Batra (2005). In this analysis, PHES was considered as an adjunct of thermal power plants, the pumping energy and transmission losses were shared by the thermal power plants and a rent for available storage capacity was paid by the beneficiaries to the PHES. This model has been proposed as an alternate to the existing method i.e. buying and selling method. The model was checked with Purulia PHES, Eastern Region in India [104]. Gupta and Panwar (2005) recommended a two part tariff system for revenue realization to a pumped storage scheme [39]. Venkateswaralu et al. (2012) proposed a practical approach for upgradation of a conventional hydro into mixed pumped storage scheme and also worked out cost- benefit analysis [102].

The published literature on Indian pumped storage schemes is very limited. Few papers discussed the optimal operation of PHES with thermal power plants by using various algorithms and power system models and a few on the economic aspects. The present research work has been exclusively carried out for Indian pumped storage schemes with particular reference to Kadamparai pumped storage plant.

1.4. AUTHOR'S CONTRIBUTION

This research work has been carried out for analyzing the status of existing pumped storage schemes in India, their operation, various constraints and future prospects. Operation of Kadamparai pumped storage plant has been analyzed in detail in this context.

- The thesis preliminarily reviews the development of the Indian pumped storage schemes, historical performance and present operating status. The analysis also examines the need for such schemes for Indian power sector for reliable power system operation and to assess various techno – economic benefits.

- The performance of the Kadamparai pumped storage plant has been analyzed in detail in this thesis by studying historical inflow, power generation and reservoir storages.

- The operation and role of reservoirs of pumped storage schemes are more significant than the conventional hydro schemes since PSS involves cyclic operation. This has necessitated study of reservoir operation of Kadamparai PSP and the operating guidelines for effective utilization of reservoirs have been developed by the use of water regulation simulation model developed for this study.

- Variable speed pumped storage operation is a new dimension in pumped storage application worldwide to improve efficiency. Hence, a study has been carried out for the variable speed operation of Kadamparai reversible pump-turbines, which can be applied during modernization and renovation of the existing turbine-generator units, since this is in operation more than 26 years. The differences in efficiency between conventional fixed speed machines and variable speed machines have been calculated to derive the benefits during generation and pumping cycles.

- The impact of introduction of new tariff mechanism i.e. Availability Based Tariff on pumped storage schemes has also been studied and presented in this thesis.

- Further, the economics of the Kadamparai pumped storage plant and major pumped storage schemes of the country have been analyzed to understand the economic status of such plants in Indian context.

- Recommendations have been made to increase the operational performance of Kadamparai pumped storage plant and for developing more pumped storage schemes in Indian context.

1.5. ORGANIZATION OF THE THESIS

The brief details of each Chapter are stated below:

The present Chapter 1 provides an overview of pumped storage schemes and about the present research, basic concepts, state of art review and author's contribution in the related area.

Chapter 2 reviews the performance of the Indian pumped storage schemes before and after the introduction of ABT. The study also examines the present status and future prospects in Indian context. The technical and economical parameters of major Indian pumped storage schemes have been analyzed in this chapter.

Chapter 3 provides description of Kadamparai pumped storage scheme, plant performance and existing operating pattern.

Chapter 4 deals with the reservoir regulation of Kadamparai pumped storage scheme by using a simulation model. The step by step simulation procedure, rule curves and operating guidelines for efficient operation are presented in this chapter.

Chapter 5 presents the variable speed pumped storage operation and the feasibility analysis of variable speed drives at Kadamparai pumped storage plant.

Chapter 6 provides the economic analysis of Kadamparai pumped storage scheme.

Chapter 7 highlights outcomes of the thesis and provides scope for future work in the pumped storage schemes in India.

Chapter 2
STATUS OF PUMPED HYDRO-STORAGE SCHEMES AND ITS FUTURE IN INDIA

2.1. INTRODUCTION

This chapter presents a critical review of the necessity of pumped storage schemes in India. This review reveals that the major constraint for pumped storage operation in India is the deficit of off-peak power available in all the regional grids except north-east region for pumping at present [61]. But the current adverse situation is likely to be gradually solved by the commissioning of newly proposed power projects. Fixing of a separate operational tariff for pumped storage schemes throughout the country is another requirement for which the government has set up a one man committee to analyze the feasibility for this peak tariff. Non-availability of lower tail pools, irrigation needs also causes poor pumping operations in some cases. However, most of the states in India are evincing interest in pumped storage schemes and proposals are being submitted to central government for securing stations clearance.

In India, planning for integration of pumped storage schemes had started in 1970's with a view to operate in co-ordination with especially nuclear plants. The first pumped storage plant of the country was commissioned in the year of 1980 – 1985 (Nagarjunasagar Pumped Storage Plant) [100]. At present, 11 pumped storage schemes with an installed capacity of 4804 MW are functioning in the country and another 1000 MW capacity plant is under construction. The Central Electricity Authority (CEA - A statutory body of Ministry of Power, Govt. of India for the technical coordination and supervision of programmes) has identified 56 potential sites suitable for the development of pumped storage schemes with a probable installed capacity of 94000 MW [43].

2.2. INDIAN ENERGY SCENARIO AND THE NEED FOR PUMPED STORAGE INSTALLATION

As per 2011 statistics, India is one of the largest energy producers in the world holding eleventh rank and approximately its consumption is 2.4% of the total energy consumption of the world. Also, India stands as the 6^{th} largest installed capacity of electricity generation and 6^{th} largest energy consumer of the world [12]. At the time of independence (15th August 1947), only 1362 MW [81] of electricity was produced in India from thermal and hydro power plants. India paid considerable attention to the generation of power since independence, as a result of which, the installed capacity of power has grown remarkably. The installed capacity of the country as on 30-04-2012 is 201637 MW comprising of Hydro (38990 MW), Thermal (133363 MW), Nuclear (4780 MW) and Renewable Energy Sources (RES) (24914 MW) [72]. Figure 2.1 shows the breakup of installed capacity with RES.

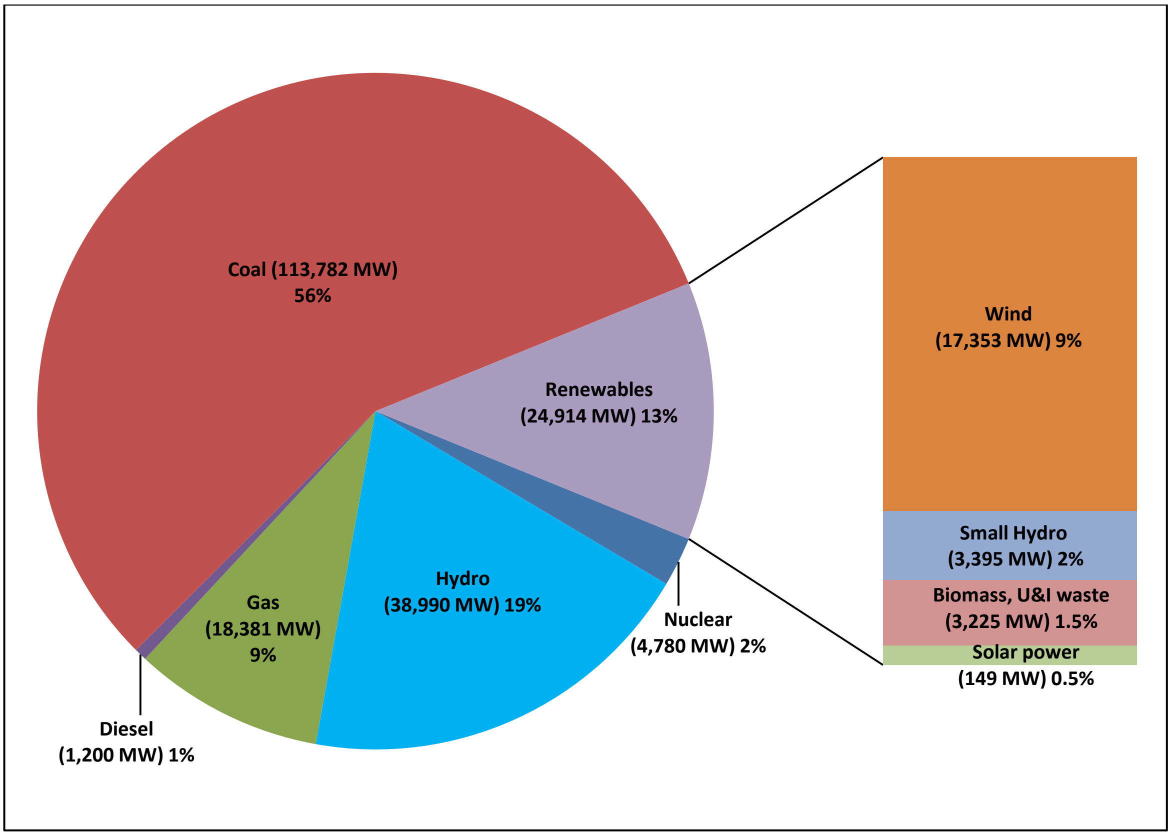
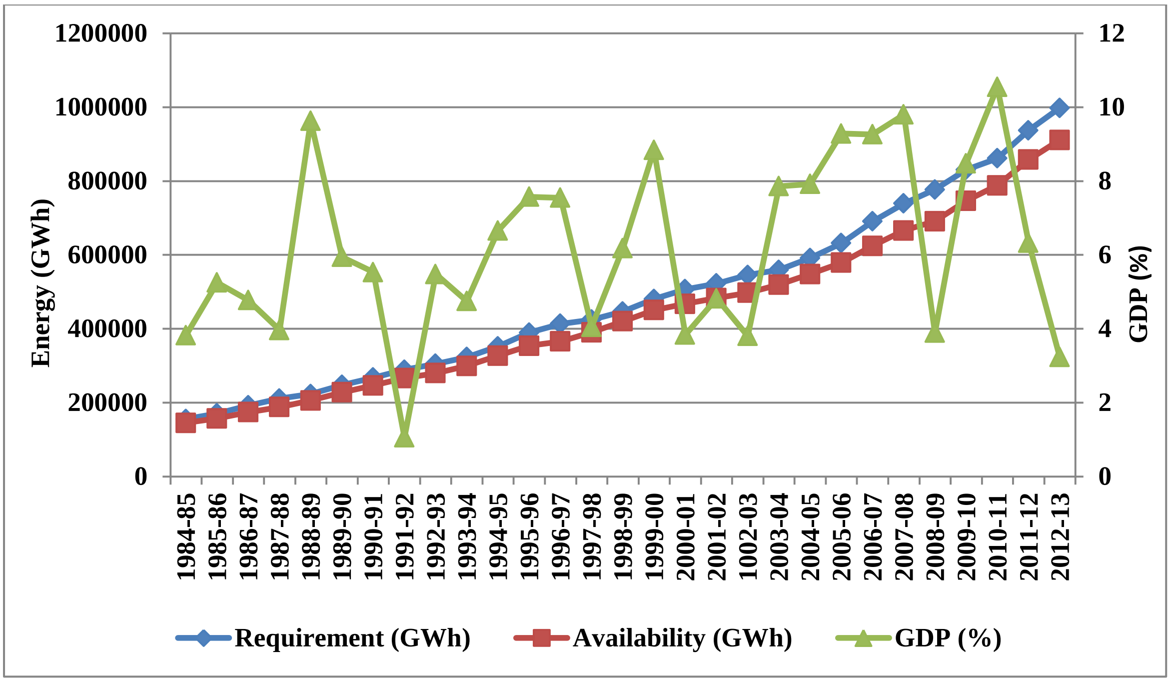


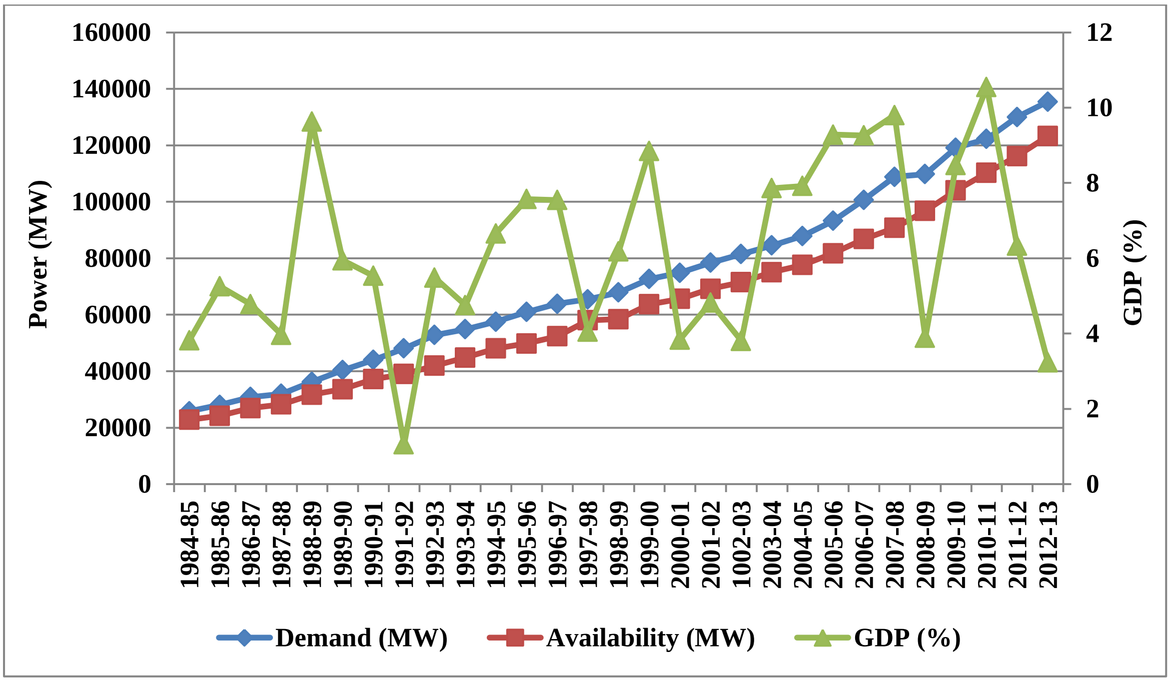
Figure 2.1 Installed capacity of the country as on 30-04-2012 [72]

It is great challenge to meet out the supply – demand gap in India due to growing economy and scarcity of the power. Energy-wise and peak-wise power supply position (1984 - 2013) of India is shown in the Figures 2.2 and 2.3. The power system in India is short of required peaking capacity by about10% and energy shortage by 15% in most of the states [66]. The growth rate of demand for power in India is higher than that of Gross Domestic Product (GDP) [27].Various planning reasons such as, over ambitious targets, delay in placement of order for main plant, delay in environment clearances, rehabilitation problems leading to litigations, geological surprises in case of hydro projects, non-availability of gas, etc have attributed to shortage of power availability in every five-year plans [2].



Source: CEA & World Data Bank

Figure 2.2 All India power supply position (Energy–Wise)



Source: CEA & World Data Bank

Figure 2.3 All India power supply position (Peak–Wise)

Besides above reasons, less output from thermal stations and reduction of inflow to the reservoirs due to monsoon failures have also causes shortage of peak power and energy availability [1]. Various schemes including ultra-mega power projects of thermal, nuclear and number of hydro projects along with RES like solar, wind and biomass based power projects have been planned and under execution by the experts during every five years plan periods [66]. The concept of the power system to meet the ever growing demand for electricity is base load demand through thermal and nuclear and to meet the peak demand using gas stations, hydro and by pumped Storage Schemes (PSS). Table 2.1 indicates the region wise hydro thermal capacity development of the country.

Right from first five year plan, the ratio of hydro thermal mix for a stable power system operation in India was taken as 40:60 by the planners [52], [73], [100]. Accordingly proposals / plans were sanctioned. Table 2.1 shows the hydro thermal mix of the country and indicates that it is not optimal in western and eastern regions. These regions have large thermal power plants. Operation of thermal and nuclear stations at high plant load factor will be difficult without support from hydro stations to take care of the peak load demands. Various studies have concluded thus the preferable capacity of the pumped storage installation for thermal dominant power system is 4-5% of the total installed capacity [59]. The region wise percentage of PSS capacity over total installed capacity is shown in Table 2.2.

Table 2.1 Region wise hydro power station installed capacity as on 30-04-2012 and PSS percentage to the total hydro capacity [72].

Region	Hydro capacity (MW)	Thermal capacity (MW)	PSS capacity (MW)	% of PSS to Hydro	% of Hydro/Thermal Nuclear mix ratio
Northern	15122.75	35071.75	1000 (under construction)	6.61	43.12
Western	7447.50	49536.79	1864	25.03	15.03
Southern	11338.03	29832.60	2000	17.64	38.01
Eastern	3882.12	22605.08	940	24.21	17.17
North-eastern	1200.00	1026.94	0	0	116.85

The above scenario clearly indicates that the stable operation of thermal and nuclear power plants is complicated due to less hydro thermal ratio. The predominant thermal base of the western and eastern regions implies energy surplus during off peak hours, which leads to plan special storage/peak plants for the stable grid operation. The development of Purulia PSS in eastern region and Ghatghar PSS in western region is ensuring optimum utilization of thermal/nuclear power available in these regions. The rise in peak load of the system in many regions except north-eastern region and increasing contribution of thermal and nuclear power often supports the energy storage installations of the country. The multipurpose (i.e. mixed type) pumped storage schemes are identified with supportive topographical settings as suitable energy storage schemes [59], [99], [100].

Table 2.2 Region wise percentage of PSS capacity over total installed capacity

Region	Total installed capacity (MW)	Installed capacity of PSS (MW)	Number of schemes	% of PSS to total capacity
Northern	54585.90	1000 (under construction)	1	1.83
Western	64894.24	1864	6	2.87
Southern	52739.93	2000	3	3.79
Eastern	26885.91	940	2	3.50
North-eastern	2454.94	0	0	0

2.3. HISTORICAL PSS DEVELOPMENT IN INDIA

In democratic India, all economical implementations have been executed through the five year plans. The history of pumped storage schemes in India has been initiated by an action plan of fifth five year plan. The 700MW Nagarjunasagar (1980 - 1985) pumped storage plant of Andhra Pradesh holds the credit of first installed pumped storage plant of the country. The 12 MW Paithan (1984) pumped storage scheme of Maharashtra is the second installed pumped storage scheme. Both these two pumped storage plants were executed by the sixth five year plan. The 400MW Kadamparai (1987 - 1989) pumped storage plant of Tamil Nadu state was commissioned during seventh five year plan. Kadana 1st stage (1x 60MW) (1990) in Gujarat and Panchet hill second unit (40 MW) under Damodar Valley Corporation (DVC) in Bihar were commissioned in 1990-91. During the eighth five year plan, Ujjain (1x12MW) (1990) and Bhira (1995) (1x 150 MW) pumped storage schemes of Maharashtra state were commissioned. One unit of Kadana 2nd stage (1x60 MW) was commissioned in March 1996 and another unit (1x60 MW) commissioned during 1998 in Gujarat. Srisailam Left Bank Power House (LBPH) pumped storage scheme (6x150 MW) in Andhra Pradesh was commissioned in the year 2001 - 2003. Sardar Sarovar Right Bank Power House (RBPH) (6x200 MW) mixed pumped storage was commissioned in 2006 in Gujarat. Purulia, a pure pumped storage plant (4x225 MW) in west Bengal was commissioned in 2007-08. The Ghatghar PSS (2x125 MW) in Maharashtra, a pure pumped storage was commissioned during 2008. The Tehri Hydro Development Corporation, a public sector enterprises of India constructing country's largest Tehri PSS of 1000 MW (4x250 MW). It is the highest capacity of mixed type pumped storage plant is under construction in Uttarakhand state and expected to be commissioned by 2016. Table 2.3 shows the historical development of PSS in the country based on five year plans [100], [101].

Table 2.3 Pumped storage growth based on five year plans in India

Plan	Installed capacity of PSS (MW)	Cumulative capacity of PSS at the end of plan (MW)
Up to 5th plan (31-3-1980)	Nil	Nil
Sixth plan (1980-85)	612 (Nagarjunasagar, Paithan)	612
Seventh plan (1985-90)	500 (Kadamparai, Nagarjunasagar)	1112
Two annual plans (90-92)	160 (Kadana Units - 1&2, Panchet hill)	1272
Eighth plan (1992-97)	222 (Kadana Unit – 3, Bhira, Ujjain)	1494
Ninth plan (1998-02)	960 (Srisailam, Kadana Unit - 4)	2454
Tenth plan (2002- 2007)	2100 (Sardar Sarovar, Purulia)	4554
Eleventh plan (2007-2012)	250 (Ghatghar)	4804
Twelfth plan (From 2012)	1000 (Tehri)	5804

2.4. PRESENT OPERATIONAL STATUS AND CONSTRAINS IN OPERATION OF PUMPED STORAGE SCHEMES IN INDIA

At present, eleven (11) pumped storage schemes are located in various states in India. Out of which, nine (9) pumped storage stations are mixed type and two (2) are pure pumped storage type. The following eight (8) stations are operated in both the modes i.e. pumping & generation as per the grid requirement: Paithan, Ujjain, Kadamparai, Srisailam, Purulia, Kadana, Bhira and Ghatghar. These pumped storage stations are operating in pumping mode for fewer hours than that contemplated in the project report due to unavailability of surplus energy in the power system for more hours. It is the prime reason for less overall output from these stations. In India, in normal days surplus power is available only during off-peak hours i.e. midnight to 5 am with limited capacity or less than the requirement of pumping capacity of the plant. During national holidays and weekends, the machines are operated as pump for more hours since low energy consumption by the industrial sector. More surplus power is available during wide spread rain in a region when energy for agricultural pumping is not required. However, daily assigned pumping and generating hours has been designed as per DPR e.g. 6 hours generation, 8 hours pumping for a day for a typical PSS has not been achieved so far. Hence, most of the PSS stations achieved 40 – 50 % of the projected design energy as mentioned in DPRs of the corresponding pumped storage plants, since the country is always facing energy shortage (Table 2.4). This table have been considered only large capacity PSS, Paithan and Ujjain PSS of 12 MW capacity have not been considered.

Nagarjunasagar, Panchet hill (DVC) and Sardar Sarovar pumped storage schemes are working as conventional hydro generators due to more inflow and commitment to irrigation needs. The tail race reservoir is under construction in respect of Nagarjunasagar and Panchet hill stations. Though these power stations have been constructed as pumped storage plants, these are being for generation only mode since more inflow is available to the respective reservoirs. However, due to upstream developments taking place at present, the corresponding reservoirs are getting less inflow. Hence, the tail race dam is under construction to develop the lower reservoir, so that these stations can also operate in pumping mode. In the case of Sardar Sarovar project, priority is given for irrigation for the period of five years and pumping operation from the station will be carried out at a later stage after stabilization of the irrigation lands in desert area [100].

Table 2.4 Hydro generation performance data (2010 - 2011), Hydro Planning & Investigation Division, CEA, August 2011 (Units are in MU)

Station	**Designed Energy**	**1996-97**	**1997-98**	**1998-99**	**1999-00**	**2000-01**	**2001-02**	**2002-03**
Purulia	1700	-	-	-	-	-	-	-
Kadamparai	797	131	150	187	143	187	163	203
Bhira	775	-	-	438	597	-	540	565
Ghatghar	410	-	-	-	-	-	-	-
Kadana	518	317	421	405	188	0	41	8
Srisailam	1400	-	-	-	-	-	381	558
Station	**2003 – 04**	**2004-05**	**2005-06**	**2006-07**	**2007-08**	**2008-09**	**2009-10**	**2010-11**
Purulia	-	-	-	-	385	670	867	878
Kadamparai	408	256	581	427	456	294	419	572
Bhira	539	580	701	-	-	-	-	-
Ghatghar	-	-	-	-	-	95	149	350
Kadana	101	362	209	352	299	78	114	118
Srisailam	328	1411	2232	2512	2546	1802	1279	1991

After introduction of Availability Based Tariff, the frequency variation could be limited within the range 49.0 – 50.5 Hz. Prior to the same (pre 2003), the variation in frequency was from below 48.0 to 52.0 Hz on daily basis [11]. The graph (Figure 2.4) shows the percentage of time of operating frequency between 49.0 Hz and 50.5 Hz pre - ABT periods, which clearly indicates the low frequency operation [26]. The design frequency of the all-reversible pump/turbine of the country for pumping operation is 49.5 – 50.5 Hz, the range fixed by the regulators. The overall unsatisfactory performance of the power sector is also reflected in the operation performance of pumped storage schemes too [93]. The main requirement for satisfactory operation of pumped storage schemes are adequate water in the tail race reservoir and frequency above 49.5 Hz with availability of required power for pumping. Seven pumped storage schemes were commissioned during the period from 1980 to 2000 and due to absence of tail race reservoir or non-availability of surplus energy in the system, pumping operations were adversely affected. Hence, mostly these PSS were operated in conventional hydro-generating mode to meet irrigation / peak demands. However, the performance of these stations in conventional mode has been satisfactory. Improvement in performance of pumped storage plants Kadamparai, Purulia and Ghatghar can be seen from the energy production data for the period from

1996 – 2011 presented in Table 2.5, which has been possible due to implementation of ABT.

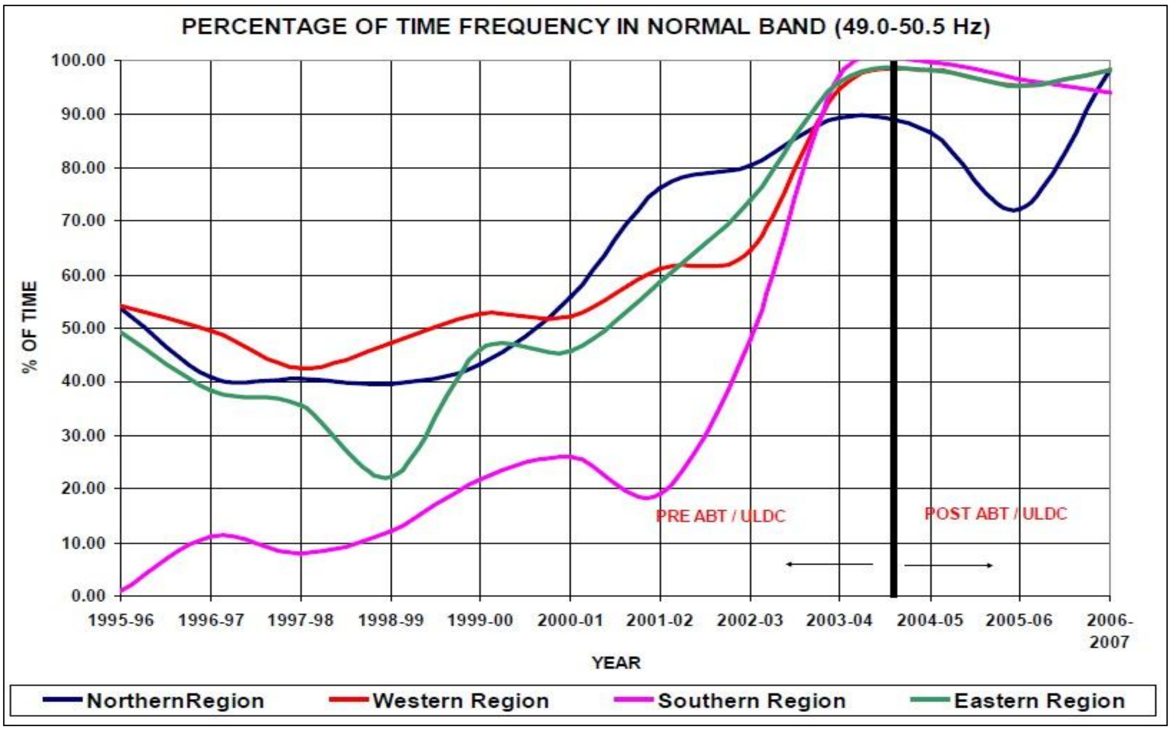


Figure 2.4 Percentage of frequency [26]

Table 2.5 Hydro generation performance data (2010 - 2011), Hydro Planning & Investigation Division, CEA, August 2011

(Units are in MU and ratio of actual energy generation to design energy is in %)

Station	**Design Energy**	**1996-97**	**1997-98**	**1998-99**	**1999-00**	**2000-01**	**2001-02**	**2002-03**
Purulia	1700	-	-	-	-	-	-	-
Kadamparai	797	131 (16%)	150 (19%)	187 (23%)	143 (18%)	187 (23%)	163 (20%)	203 (25%)
Ghatghar	410	-	-	-	-	-	-	-
Station	**2003 – 04**	**2004-05**	**2005-06**	**2006-07**	**2007-08**	**2008-09**	**2009-10**	**2010-11**
Purulia	-	-	-	-	384 (23%)	669 (39%)	867 (51%)	878 (52%)
Kadamparai	408 (51%)	256 (32%)	581 (73%)	427 (54%)	456 (57%)	294 (37%)	419 (53%)	572 (72%)
Ghatghar	-	-	-	-	-	95 (23%)	149 (36%)	350 (85%)

2.5. ECONOMIC ANALYSIS OF INDIAN PUMPED STORAGE SCHEMES

In developed countries, the operation of pumped storage is based on price-based mechanism, since they have sufficient surplus and various operating arbitrages with incentives for the independent generators. In such environment, the schemes are designed to buy cheap off-peak energy from the grid for pumping and sell the energy during peak hours at a competitive price, which is higher than purchase price. Indian power industry has not yet commenced such a commercial operation of pumped storage, since cost of common off peak power for pumped storage is yet to be fixed [91], [101]. However, an economic analysis has also been carried out for Indian pumped storage schemes since these are the only bulk energy storage schemes for the country. Various costs involved in pumped storage operation in Indian context are analyzed briefly in the following chapter.

2.5.1. Costs Involved in PHES Operation in India

Evaluation of PHES development during planning stage was carried out based on site condition, investment cost, and possible operating hours on both modes and considering the marginal cost of production from thermal power stations. The following Table 2.6 shows the capacity and investment of 6 major PHES of India.

Table 2.6 Capital cost of major PHES [37], [79], [90]

Sl. No.	Name of PHES	Installed capacity (MW)	Commissioned year	Capital cost (Million Rupees)	Capital cost adjusted to 2013 (Million Rupees)
1	Kadamparai[a]	400	1987	2250	13809.3
2	Srisailam	900	2003	26200	51602.7
3	Ghatghar[a]	250	2008	19280	23751.2
4	Purulia[a]	900	2008	26388.2	36734
5	Kadana	240	1998	3425	7997.1
6	Bhira	150	1995	2570	6943.3

[a] Data collected from plant authorities

The cost of commissioning of various PHES has been adjusted to the year 2013 with inflation by using wholesale price index of India. Out of 11 commissioned PHES, only 6 schemes are presented in the table. Paithan and Ujjain PSS of 12 MW capacity have not been considered due to its very low contribution to the grid. As the tail race reservoirs are under construction in Nagarjunasagar and Panchet hill PHES, they have also not been considered. The 1200 MW Sardar Sarovar PHES is being operated as a conventional hydro generator due to more inflow and commitment to irrigation needs and hence it is also not considered. It is also observed from the Table 2.6, that the investment cost is different for Srisailam and Purulia even though they have same installed capacities which can be attributed to the site specific conditions usual with hydropower stations.

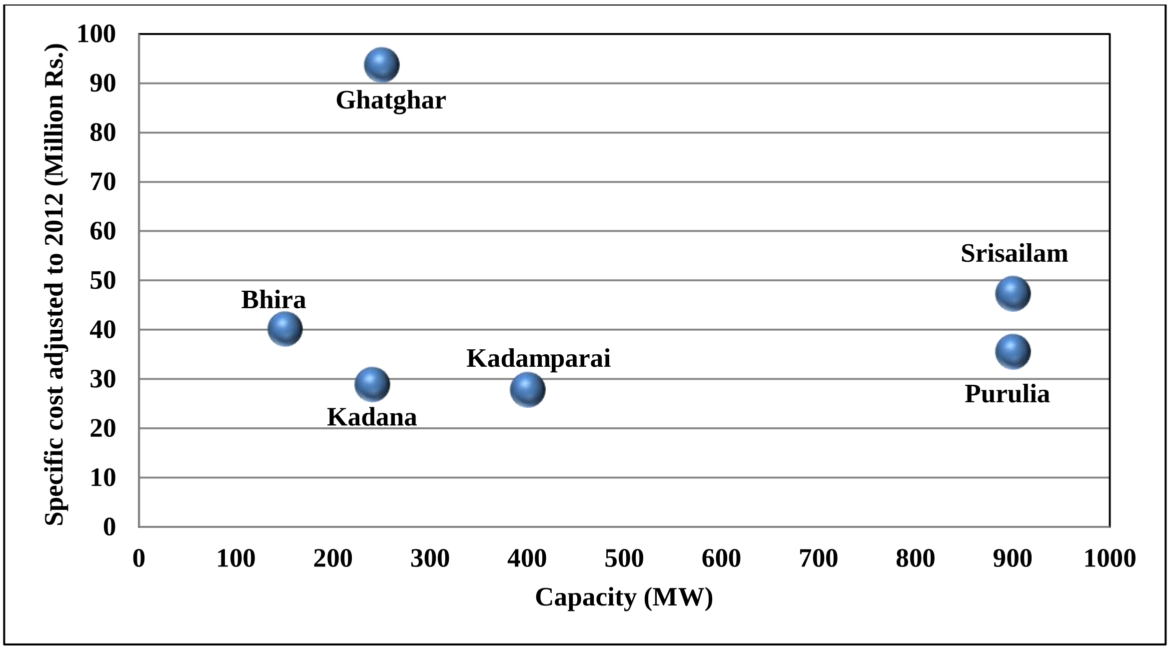


Figure 2.5 Capital cost/MW for major PHES

The specific cost (Rs./MW) of 6 PHES in India is shown in the Figure 2.5 The specific cost varies from Rs. 33 Million to Rs. 57 Million for the above stations except Ghatghar, where it is Rs. 95 Million. Ghatghar and Purulia are pure PHES which are commissioned recently and their capital cost includes all the components such as dams, transmission lines, water conductor system, hydro-electric, hydro-mechanical systems, etc. The other plants are mixed PHES where either upper or lower or both the reservoirs were already available [refer Annexure - 2]. Generally, specific cost of smaller power plants is higher than the larger power plants. The site specific reservoir volume and L/H ratio are also major parameters for determining PHES' capital cost. Hence the specific cost of the Ghatghar is high. Further, general escalation in input costs [105], additional cost involved in restoration after natural disaster during construction period and other inflationary factors have been the causes for higher specific cost for same plants as compared to others.

Generally, three costs are involved in PHES operation i.e. the generation cost, cost for pumping energy and cost for other operational benefits such as VAR regulation, etc. The first two costs decide the regular economics of PHES. The third one is usually complex in nature and has not been considered in this study since very less synchronous condenser operation of PHES was recorded. Capital investment and operation and maintenance (O&M) cost determine the production cost of the station based on the design energy and it varies based on the actual operation.

The production cost based on design energy to the capital investment for three regions (east, west and south) has been calculated for four major PHES in India and is shown in the Table 2.7. Out of the four schemes, two are mixed type and other two are pure storage schemes. 20% of the capital investment has been assumed as annual expenditure i.e. annual fixed cost (AFC). The investment costs during different years have been converted into the cost as per 2013 by using wholesale price index of India. The production cost has been worked out for energy produced equal to 100%, 75% and 50% of the projected design energy.

Table 2.7 Generation cost based on designed energy to capital investment

Description	Kadamparai	Srisailam	Purulia	Ghatghar
Installed capacity (MW)	4 x 100	6 x 150	4 x 225	2 x 125
Year of commissioning	1987	2003	2008	2008
Type	Mixed	Mixed	Pure	Pure
Design energy (MU)	797	1400	1700	470
Capital investment on commissioning (Rs. x 10^7)	225	2620	2638.82	1578.90
Capital investment adjusted to 2013 (Rs. x 10^7)	1380.93	5160.27	3673.40	2375.12
Annual Fixed Charge (AFC) (@20% of Investment) (Rs. x 10^7)	276.19	1032.05	734.68	475.02
Cost/KWh (in Rs.)				
For 100% DE (Design Energy)	3.47	7.37	4.32	10.11
For 75% DE	4.62	9.83	5.76	13.48
For 50% DE	6.93	14.74	8.64	20.21

The cost of energy produced from PHES depends upon the following factors:

- Available head (m) for operation and topography of both the reservoirs.
- Plant utilization factor.
- Capital cost.
- Cost of pumping energy.

The cost of pumping energy was not separately shown in expenditure account of the station, but found included in the overall expenditure of the concerned state electricity board's account e.g. Kadamparai pumped storage plant.

Production costs based on actual generation of the plants are shown in Table 2.8. Investment cost has been considered as on the commissioning year and hence inflation has not been added. The results show that the gradual increase in plant performance reduces the generation cost.

Table 2.8 Generation cost based on actual annual energy generation to capital investment

Generation cost (in Rs/kWh) for 20% AFC						
Station	**2001-02**	**2002-03**	**2003-04**	**2004-05**	**2005-06**	**2006-07**
Purulia	-	-	-	-	-	-
Ghatghar	-	-	-	-	-	-
Srisailam	13.75	9.39	15.98	3.71	2.35	2.09
KPSP	2.88	2.22	1.10	1.76	0.77	1.03
Station	**2007-08**	**2008-09**	**2009-10**	**2010-11**	**2011-12**	**2012-13**
Purulia	13.74	7.89	6.09	6.01	-	-
Ghatghar	-	33.24	21.19	9.02	-	-
Srisailam	2.06	2.91	4.09	2.63	-	-
KPSP	0.98	1.53	1.07	0.79	0.89	-

The above operating costs are calculated only by considering the generation cost. But pumping cost is the major factor, which determines the real economics of a pumped storage plant. The economic aspect of pumped storage schemes on pumping operation in India prior to restructuring of power industry or in the present young liberalized market is not recorded in the respective stations. The reason is all the commissioned PHES prior to restructuring are mixed storage schemes, which are operated as conventional hydro generating stations most of the times and for very less duration are operated in pumping mode. Further all the commissioned PHES of the country except Bhira PHES (IPP – Independent power producer) have been operated by the concerned state governments for their intrastate needs and price based operations do not exist in India. The economics of the PHES calculated by the authorities like conventional hydro power stations i.e. sale cost fixed as average cost per kWh of the respective state based on the revenue earned, and the pumping energy cost is mostly adjusted with the total revenue of the state electricity board as other expenditure.

2.6. FUTURE PROSPECTS

As mentioned earlier, CEA has identified 56 potential sites suitable for development of pumped storage schemes. Figure 2.6 shows the potential PSS sites in India and Table 2.9 indicates the region wise capacity available for PSS development.

Before developing new pumped storage schemes, it is necessary to establish the need for a pumped storage scheme in relation to the total installed capacity and maintaining the base rule of peak load plant to base load plant mix ratio as 40:60. Study reports suggest the optimum installed capacity of pumped storage in a predominant thermal/nuclear would be in the order of 4 to 5% of the total installed capacity [59].

Table 2.9 Region wise distributions of identified pumped storage schemes

Region	No. of identified schemes	Probable installed capacity (MW)
Northern	7	13065
Western	25	38220
Southern	8	16650
Eastern	6	9085
North-Eastern	10	16900

Increase in RES utilization is another major area of Indian energy sector. The total estimated potential of renewable energy of the country is around 85000MW from commercially exploitable sources, i.e., wind, small hydro and biomass/bio-energy excluding solar energy [60]. In 2011- 12 installed capacity of renewable sources has represented nearly 13% of the total installed capacity.

The notable renewable energy in India is the wind energy. Worldwide, the increasing trend of commissioning of wind power plants in power systems is found and it is considered as more commercially viable as compared to other renewable energy sources [62]. The stochastic nature of the wind energy can be managed by combining with energy storage schemes [45]. As on April 2012, 17353 MW installed capacity of wind energy has been established in the country. Now India is the fifth largest wind power producer in the world. Apart from the above installed capacity, the estimated wind energy potential of the country is 49130 MW [3]. The efficient utilization of renewable energy can be achieved by coupling the same with pumped storage systems. Similarly, pumped storage schemes can play a vital role in the production of electricity from solar energy (photovoltaic and thermal routes) [22]. The Table 2.10 shows the development of grid connected renewable power in India [28].

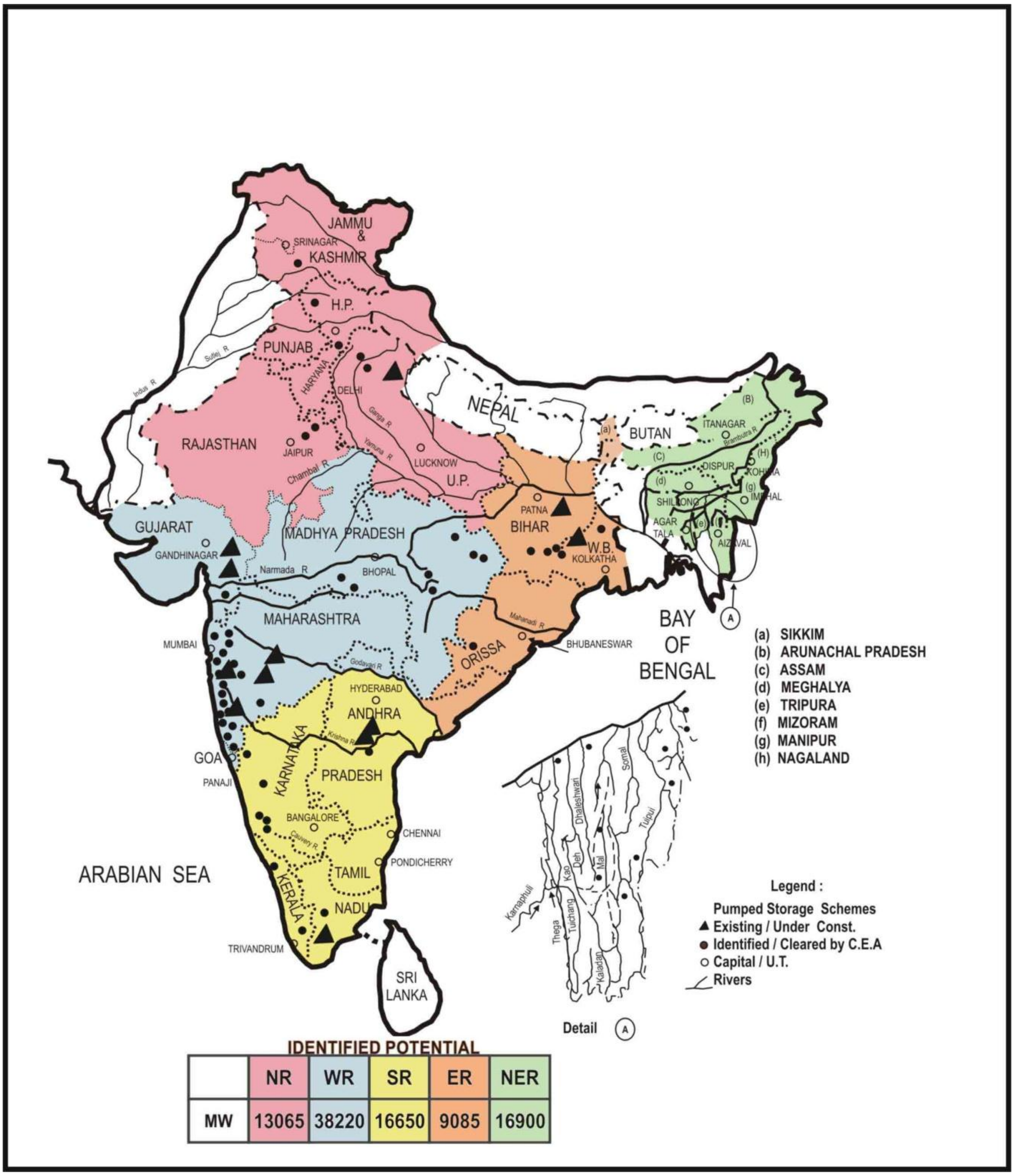


Figure 2.6 Existing schemes and region wise identified sites

Dudhani (2006) et al. [27] highlighted the gap between peak load power demand and availability of power at the regional level, also analyzed how this gap could be bridged by utilizing nation’s renewable sources. The analysis and mathematical model reveal surplus energy in all the regions if the renewable energy potential could be tapped to the power grid as utilizable energy and allocated in optimal way since all the grids are interconnected. The major reason for lack of pumped storage operation is the deficit of surplus power for pumping operation. If the above scenario persists i.e. the planned capacity of renewable energy sources executed in future, the pumping operation could be carried out efficiently and it would increase the overall system efficiency.

Table 2.10 Development of grid – connected renewable power in India (in MW) [28]

Five year plan	Achieved		In Process	Anticipated	Targets
	Bye the end of the 9th plan (cumulative installed capacity)	10th Plan (additions during plan period)	Anticipated in the 11th plan (additions during plan period)	By the end of the 11th plan (cumulative installed capacity)	By the end of the 13th plan (cumulative installed capacity)
Years	Through 2002	2002 – 2007	2007 – 2012	Through 2012	Through 2022
Wind	1667	5415	10500	17582	40000
Small Hydro	1438	520	1400	3358	6500
Biomass	368	750	2100	3218	7500
Solar	2	1	1000	1003	20000
Total	3475	6680	15000	25161	74000

2.7. SCHEMES CLEARED BY CEA

Only two pumped storage schemes have gone through all the processes laid down by CEA and the remaining proposals are in planning stage. The two projects are namely, 1000 MW Tehri – II stage in Uttarakhand and the 80 MW Koyna pumped storage scheme in Maharashtra.

The Tehri project is under construction and expected to be commissioned by 2016. This project is noteworthy because for the first time in the world, a turbine-pump has been designed to cater to the largest head variation in the world. Initially, the plant was planned to adopt two speed variable drives for utilizing this high head variations which has been subsequently changed to adopt doubly fed induction generator for variable speed operation [32].

2.8. CONCLUDING REMARKS

The pumped storage plants so far established in the country have not been able to function as projected due to non-availability of surplus energy in the power system to meet the pumping power needs.

In developing economies, where energy demand grows incrementally, it becomes increasingly difficult to bridge the gap between demand and supply. In such a scenario, it becomes extremely difficult to attain a state of surplus energy supply. Hence, planning for pure pumped storage schemes need to be considered with due caution.

With increased harnessing of renewable energy sources like wind and solar, storage of energy plays a vital role for effective utilization of energy produced from such sources. Under this scenario, development of pumped storage schemes needs to be considered.

In future, for reservoir based hydropower developments, it may be worthwhile to plan for about 20-25% of capacity for mixed mode operation. Such a situation would insulate the power plant from reduced capacity utilization in the event of lesser inflow into the reservoir due to increased upstream utilization of water and also helps in storage of energy produced from renewable energy sources for use at a later time of need.

Planning for development of pumped storage schemes need a detailed study of the power system regarding availability of surplus energy, and only after the same is established, implementation should be taken up. Such a calculated strategy can only ensure projected performance bench-mark and financial efficiency.

Chapter 3
STUDY AREA – KADAMPARAI PUMPED STORAGE PLANT

3.1. INTRODUCTION

The Kadamparai pumped storage scheme of Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO – Formerly known as Tamil Nadu Electricity Board (TNEB)), Tamil Nadu, India was commissioned in 1986 with an initial capacity of 100 MW. The plant's operating capacity has been enhanced to 400 MW (100 MW x 4 units) in the year 1988 - 89. It is a mixed pumped storage plant located in Coimbatore district of Tamil Nadu state, Southern India. It was planned and designed as a cavern power house so as to have minimal environmental impacts. The plant has the distinction of first pumped storage plant in India which operated on pumping and generation modes. It represents 10% of the total capacity of the Tamil Nadu when it was commissioned. It has been designed to store the excess energy from nuclear, thermal and hydro plants in the state and to meet the load during the peak hours. The location of the Kadamparai pumped storage plant is shown in the Figure 3.1.

Reservoirs, water conduit system and the power house are the three major elements for any pumped storage system. These three elements of the Kadamparai pumped storage scheme are explained in the following sections. Besides the above, the operational pattern of the plant, its historical performance, operational constraints and study on the need to improve the plant performance are also discussed.

3.2. RESERVOIRS

The upper reservoir of the Kadamparai pumped storage plant (KPSP) is on Kadamparai river and the lower reservoir is on the Aliyar river. The Kadamparai river is the tributary of the Aliyar river. The pumped storage scheme has been developed later with the existing Upper Aliyar reservoir. Kadamparai dam was built as a part of the pumped storage scheme during 1979 – 84. The Aliyar river already has two reservoirs i.e. Upper Aliyar and Lower Aliyar reservoirs, which were built during 1962-70. The upper Aliyar reservoir located in Anaimalai Hills acts as the lower reservoir of the pumped storage scheme. It has a power plant of 60 MW capacity built in 1962. The lower Aliyar reservoir has also a mini hydro plant for the capacity of 2.5 MW (2 x 1.25). The tail water released from the power generating unit of the Lower Aliyar reservoir is used to irrigate the command area located downstream of the reservoir and it is under the control of public works department (PWD). The locations of these cascaded reservoirs are represented in Figure 3.2.

Figure 3.1 Location of Kadamparai pumped storage plant

The natural flow of the main stream and tributaries of the Aliyar river is diverted through the weirs such as Vandal dam, Akkamalai dam and Deviar dam through a 3558 *m* long diversion tunnel to create a pool for a pumped storage operation at Kadamparai reservoir. The maximum discharge capacity of the diversion tunnel is 42.58 m^3/sec. The diversion of the water from the weirs has increased the catchment area of the Kadamparai dam from 22.75 km^2 to 83 km^2. The layout of the Kadamparai pumped storage project on the Aliyar river along with other cascaded reservoirs are shown Figure 3.3.

The Kadamparai reservoir (Upper dam of PSP) is located at the elevation of 1149 *m* has a gross storage capacity of 30.8 × 10^6 m^3 and a live storage of 26.8 × 10^6 m^3. The height of the dam is 67.5 *m*, and the crest length is 808 *m*. The maximum flood discharge capacity of the dam is 518 m^3/sec. The Upper Aliyar reservoir (Lower dam of PSP) is located at the elevation of 770 *m* and has a live storage capacity of 21 × 10^6 m^3. The available head at Upper Aliyar dam is 1475 *ft*.

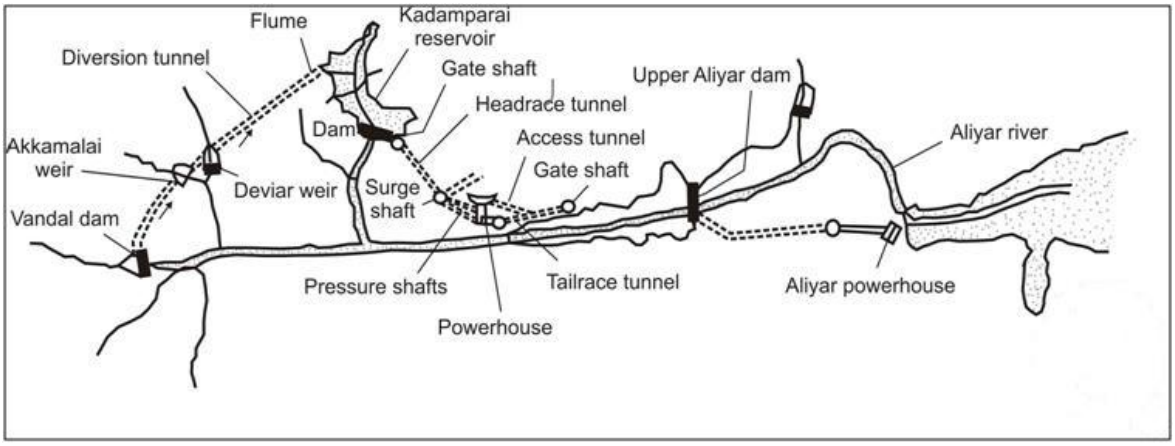


Figure 3.2 Layout of the Kadamparai pumped storage project on the Aliyar river

3.3. WATER CONDUIT SYSTEM

A 1222 *m* long, 7 *m* diameter, 150 m^3/sec. capacity head race tunnel is used to draw the water from the upper reservoir i.e. Kadamparai reservoir. A head race surge shaft with 83 *m* height, 15 *m* diameter with restricted orifice type bell mouth arrangement is located at the end of this head race tunnel. Two pressure shafts of 507 *m* length each and 4.5 *m* diameter inclined at an angle of 51° to the horizontal have been excavated beyond the surge shaft well. The discharge capacity of these pressure shafts is 75 m^3/sec. Further, these two pressure shafts bifurcate near the underground powerhouse cavern and forming four penstocks with 3 *m* diameter and 37.5 m^3/sec. discharge capacity. The power house 200 *m* below the ground level is housing four reversible turbine-generator units with the dimension of 128.5 *m* long, 20.4 *m* wide and 33 *m* high. The tailrace tunnel which is used to deliver the discharge from the powerhouse to the Upper Aliyar reservoir is 1476 *m* long, 7 *m* diameter and 150 m^3/sec. discharge capacity [6].

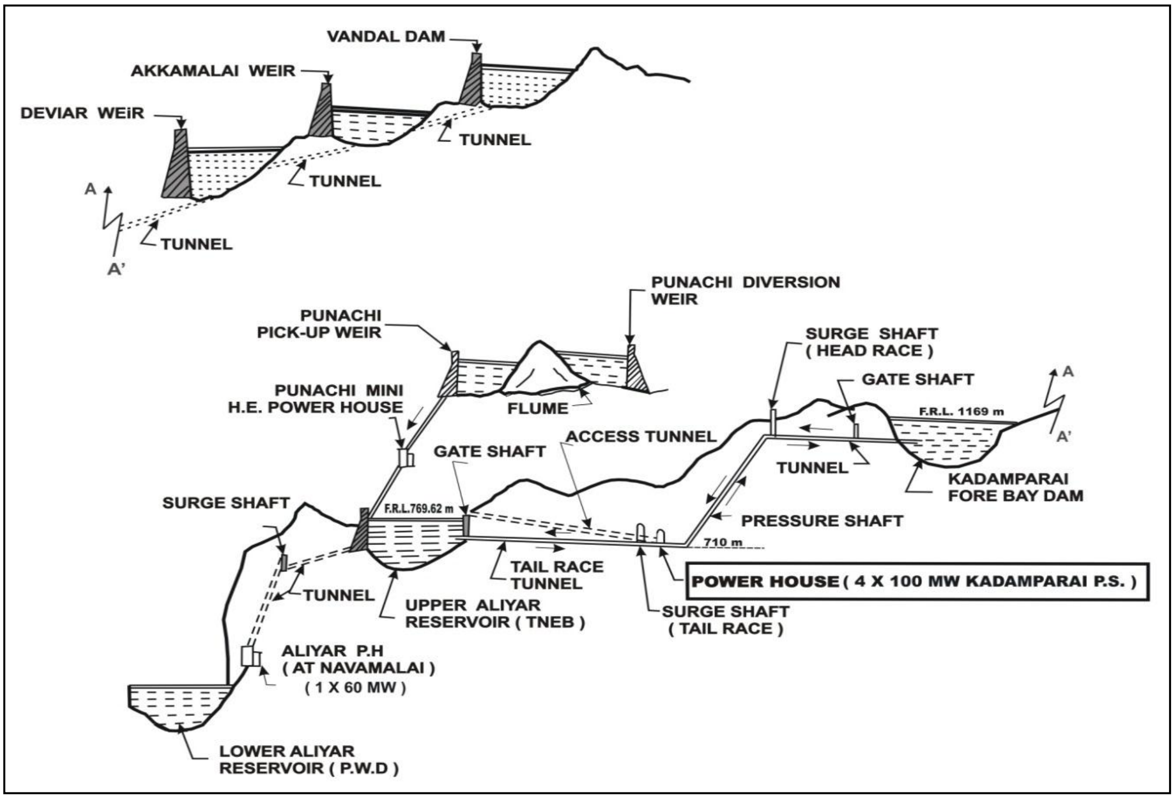


Figure 3.3 Kadamparai pumped storage scheme

3.4. POWER HOUSE

A cavern power house located in between Kadamparai and Upper Aliyar reservoirs has four reversible pump turbine Francis units. The major components of the power house and technical specifications of the Kadamparai pumped storage scheme are discussed in the following subsections.

3.4.1. Electromechanical system

The Kadamparai Power House is equipped with four reversible Francis turbines. The distributor centerline of each unit is at the elevation of 710 *m*. The first unit was commissioned by BHEL (Bharat Heavy Electricals Ltd., India) in the year 1986 - 1987 turbine supplied by Boving and generator by GEC of UK. The remaining three units were manufactured and supplied by BHEL, Bhopal, India. All the reversible units are designed to operate under the net head of 341 *m* in the turbine mode and 381 *m* in the pump mode. The rated capacities of the machines are 102 MW and 107 MW as turbine and pump respectively.

3.4.2. Generator / Motors

The capacity of generator/motor is 111.1 MVA as generator and 111.224 MVA as motor and is at an operating power factor of 0.9 and 0.95 respectively. The generation voltage of each unit is 11kV and the static excitation system operates at 222 V DC (Direct Current) and 852 Amps field current.

The following two methods are adopted for starting the synchronous machine on pump mode.

- Back to back starting.
- Static Frequency Converter.

3.5. TECHNICAL SPECIFICATIONS

3.5.1. Upper reservoir (Kadamparai reservoir)

Full reservoir level (FRL)	1149.0 *m*
Minimum draw down level (MDDL)	1112.0 *m*
Catchment area	22.79 km^2
Gross storage at FRL	1080.9 Mcft
Storage at MDDL	140.5 Mcft
Height of dam	67.5 *m*
Maximum flood discharge	517.8 $m^3/sec.$

3.5.2. Lower reservoir (Upper Aliyar reservoir)

Full reservoir level (FRL)	769.62 *m*
Minimum draw down level (MDDL)	745.24 *m*
Catchment area	46.8 km^2
Gross storage at FRL	937.89 Mcft
Storage at MDDL	195.5 Mcft
Height of dam	80.77 *m*
Maximum flood discharge	1528 $m^3/sec.$

3.5.3. Penstock

Number of branches	4
Size	3 *m* diameter
Length	38 *m* (each penstock)
Capacity	37.50 m^3

3.5.4. Head race tunnel

Sill level at entry	1102 *m*
Section circular	7 *m* diameter
Length	1222 *m*
Capacity	150 m^3

3.5.5. Pressure shaft

Size	4.5 *m* diameter
Length	507 *m*
Capacity	75 m^3

3.5.6. Tailrace tunnel

Sill level at entry	EL 745.25 *m*
Section circular	7 *m* diameter
Length	1476 *m*
Capacity	150 m^3

3.5.7. Turbines

Type	Vertical, Mixed flow, Francis reversible
Rotational speed	500 RPM
Number of units	4
Runner discharge diameter	3296 *mm*
Specific speed generation (metric)	127
Rated head (generation/pumping)	341 *m*/381 *m*
Design flow (turbine/pump)	34 m^3/26.2 m^3
Output at rated head (turbine/pump)	102 MW/107 MW

3.6. OPERATIONAL PERFORMANCE

The Kadamparai pumped storage plant has been designed to operate based on daily, weekly and seasonal scheduling. The daily load curve of Tamil Nadu generally represents morning peak demand, evening peak demand and slack time during night. The operation schedule of the Kadamparai PSS always depends on the load pattern as mentioned above. During first ten years of operation, the performance of the plant was below projected level due to low grid frequency, i.e. grid operated mostly at frequency below 49Hz. Since most of the time, the frequency remained below 49 Hz, no surplus power was available for pumping operation. Hence generation in pumping mode was adversely affected, causing overall poor performance. However, during monsoon periods, the station was operated as a conventional hydro generating station using the monsoon run-off and grid requirement. Mainly the pumping operation was carried out during weekends and on national holidays. Further a major fire accident occurred in the transformer cavern in the month of October 1990 causing major outage of the station. The plant was brought to full capacity i.e. 400 MW after a major renovation in the year 1997. Hence the plant's contribution as a pumped storage plant has been very low till the year 2000. 'Availability Based Tariff' was introduced on 1st Jan 2003 in the southern regional grid. After the introduction of ABT, improvement in frequency occurred, resulting in pumping operation during night hours. Contribution by the KPSP station in both modes has increased thereafter. The generation and pumping performance of the plant after ABT is shown in the Figures 3.4 and 3.5 and the overall operational performance of Kadamparai plant is illustrated in Figure 3.6 from 1987 – 88 to 2011 – 12.

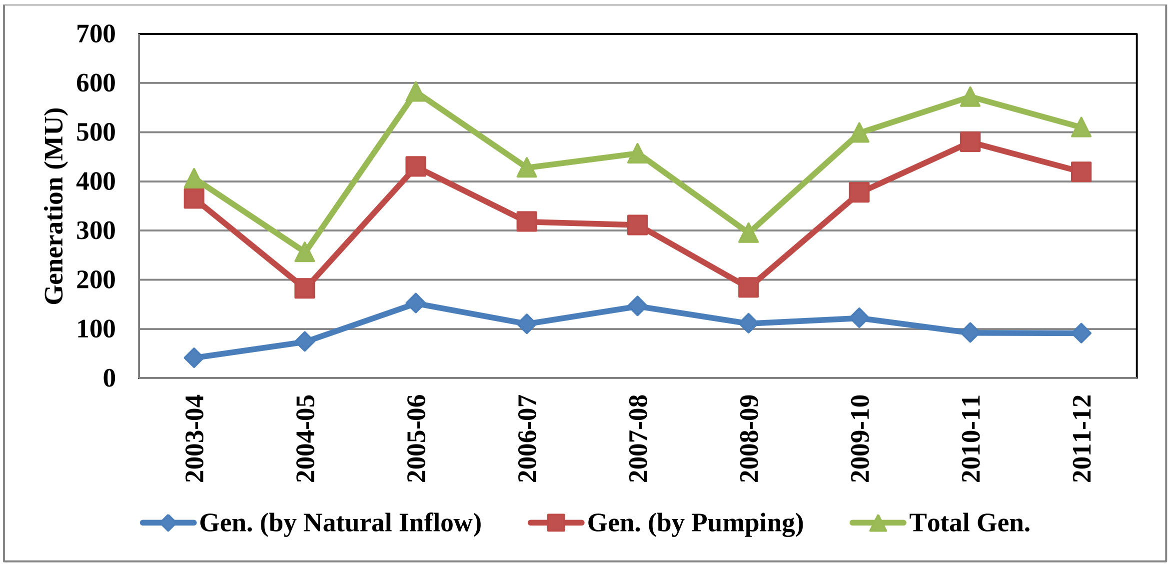


Figure 3.4 Generation of Kadamparai after ABT

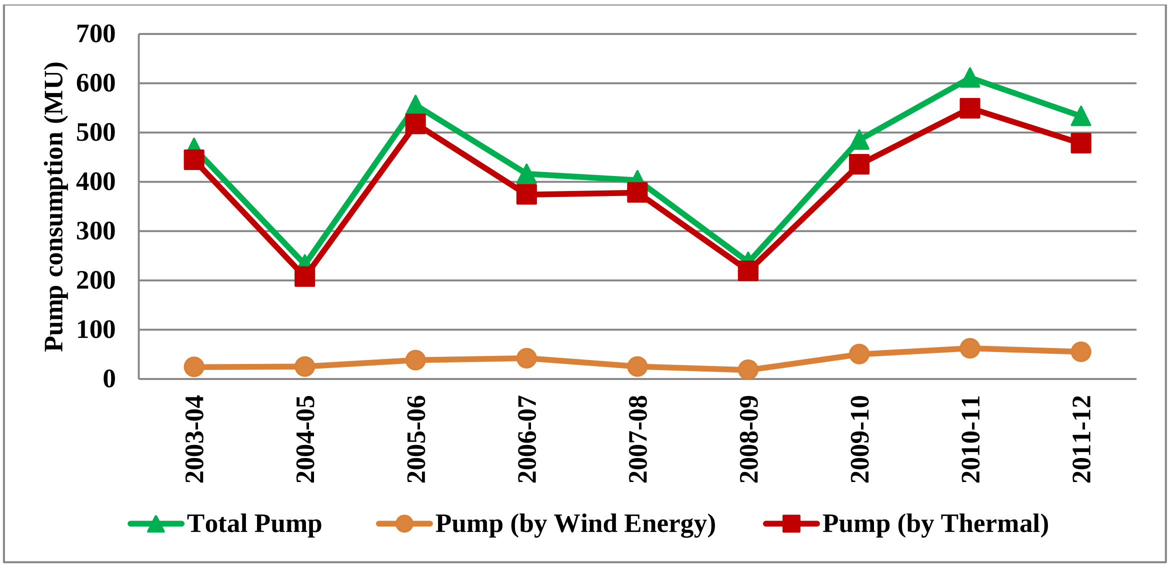


Figure 3.5 Pumping of Kadamparai after ABT

Energy projected as per the DPR of Kadamparai pumped storage plant is 797 MU i.e. 6 hours generation and 8 hours pumping for about 300 days in a year including the energy generated from the natural inflow. 581 MU generated during 2005 - 06 is considered as highest energy generated since the inception of the plant. Further, load shedding has been a regular feature from 2008 due to rapid increase in demand which has been reflected in the plant performance of KPSP. As a result, the plant generated only 292 MU with the increase of power cut from 10% to 40% in 2008-09, as insufficient power to operate all the 4 machines for pumping was available. The generated output and its percentage to the DPR-value are shown in figure 3.6. Gradual addition of wind power plants capacity has been brought into the grid from 2001 onwards and surplus energy from wind is being utilized through this pumped storage plant. Wind energy utilization has contributed increased power input for pump operation and thereby increased output in power contribution to the state grid during peak and emergency periods. The increase in power output after 2008 - 09 is evident from figure 3.5.

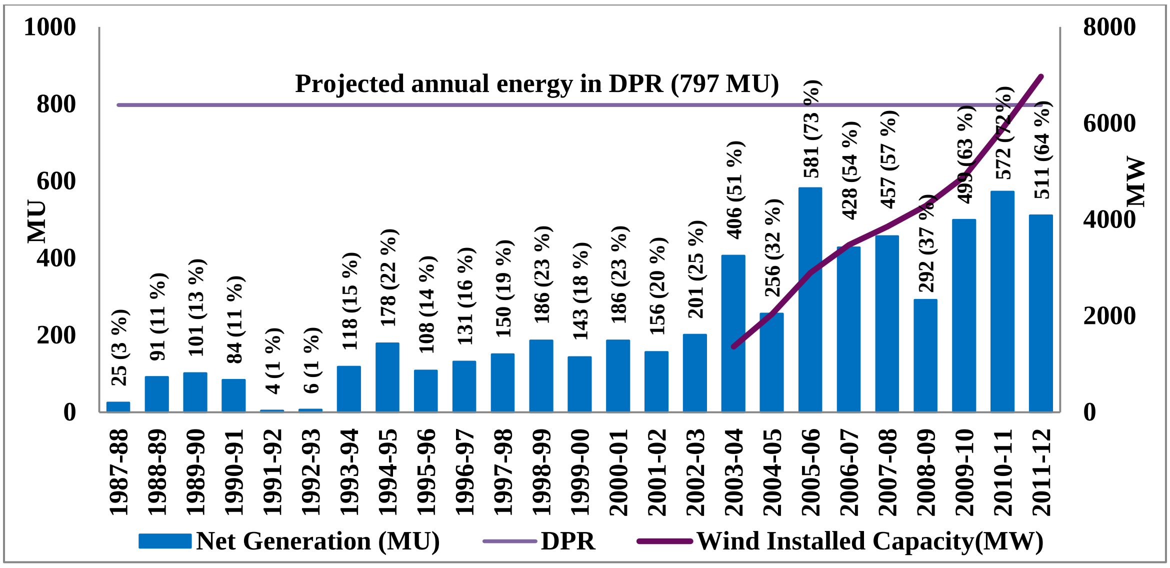


Figure 3.6 Operational performance of Kadamparai

3.7. OPERATING PRACTICE

The following facts have been observed from the above plant performance analysis and historical operational pattern,

- The plant is mainly used for peaking purpose as storage plant. It is being operated during morning peak and evening peak as generator and utilized for pumping during slack hours of Tamil Nadu state grid.
- Apart from the above peaking operation, it is also used for emergency periods such as plant outages if any in the power system.
- Pumping used to carry out at the time of surplus power available in the grid during night in regular days and during day time mostly in weekends.
- Operated one or two units for more hours as conventional hydro power plant at the time of high monsoon periods.
- It is also observed that the plant has been operated as synchronous condenser for limited hours in past records.
- The plant is mainly operating based on daily and weekly cycle of the load curve of the state grid and utilized as a last tool in merit order dispatch.
- Combined storage (sum of upper and lower reservoir storage) of 1600 Mcft to 1800 Mcft is maintained during monsoon periods of the year and gradual reduction of combined storage to 800Mcft to 1000 Mcft is maintained for flexible plant operation.

- No standard operating/scheduling procedure or practice is adopted for this station. Hence, it always follows the load despatch centre's commands being a reserve plant of the power system.

3.8. LIMITATIONS OR OPERATING CONSTRAINTS

1. Full reservoir level during monsoon period in both the reservoirs imposes restriction on generator or pump operations.
2. Discrete operation: Change of generation to pumping mode and vice versa causes more start and stop of units.

   Normally the station experiences about 6 to 8 start and stop operation of each unit per day. Due to frequent start and stop operation, wear and tear loss of machine parts is reported and increases the machine outage periods.
3. Maximum reservoir capacity is to be maintained at both upper and lower reservoir, for flexible operations in all time during monsoon periods without surplus i.e. spill.

   But it is not possible to operate the plant without surplus during high inflow periods. Surplus is recorded in lower reservoir due to the operation of Kadamparai pumped storage plant since inflow to upper reservoir is utilized for generation and hence no spill is recorded in upper reservoir.
4. 50 Mcft per day discharge is the limit in Aliyar power house.

   This discharge constraint of lower reservoir sometimes restricts generation operation of Kadamparai during monsoon and higher inflow periods. Spill is occurred whenever Kadamparai machines are operated on generator mode either to meet grid demand or to use high monsoon inflow effectively for power generation.
5. Minimum water is to be maintained in both the reservoirs to meet grid demands during summer periods.

   April and May is considered as emergency period for the plant, at that time, more thermal/nuclear station failures are recorded. Hence, full utilization of the reservoir either for generator or pump in summer affects the emergency operation of the plant.
6. Surplus power of the order of 110 MW, 220 MW, 330 MW and 440 MW at a frequency above 49.7 Hz is required for pumping operation of one to four units.

   So far the criteria of eight hours pumping operation in a day for 300 days in a year as conceived in the detailed project report (DPR) has not been achieved due to less surplus power input available from the grid.

3.9. NEED FOR IMPROVEMENT OF PLANT PERFORMANCE

Kadamparai pumped storage plant is the only pumped storage plant of TANGEDCO. The total installed capacity as on 01.04.2012 of Tamil Nadu state is 10364.54 MW. The generation profile of Tamil Nadu state is shown in the following Figure 3.7. In addition to this installed capacity, 7791 MW renewable energy sources are also available in Tamil Nadu grid in which wind energy is a major renewable energy source of Tamil Nadu state accounting for 6970 MW. In Tamil Nadu maximum wind energy is available during April to September [20]. Peak and energy shortage are the major problems in India and almost it exists all regional grids except north-eastern grid. In Tamil Nadu, peak and energy shortage is the major problem and hence load shedding is implemented to meet supply-demand gap. The peak and energy shortage of India and Tamil Nadu is shown in Table 3.1.

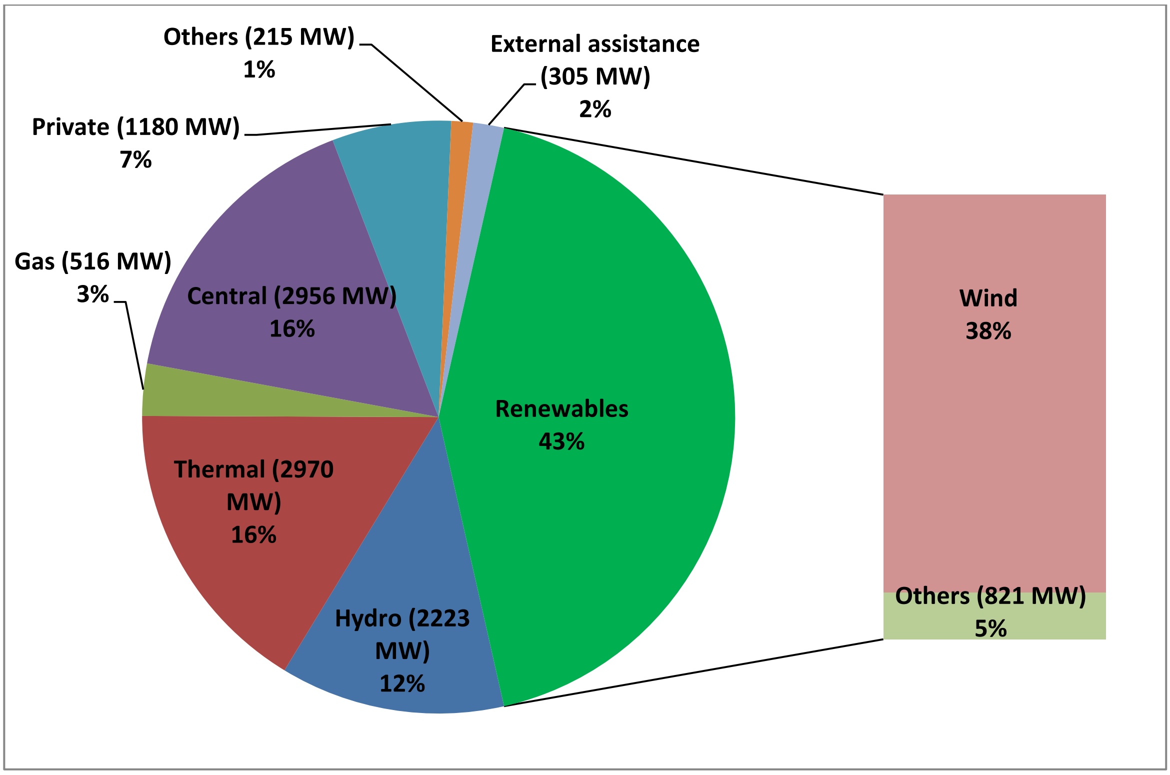


Figure 3.7 Generation scenario of Tamil Nadu State [20]

Table 3.1 Peak and energy shortages of Tamil Nadu state & India [5], [4], [29], [77]

Year	India		Tamil Nadu	
	Energy shortage (%)	Peak shortage (%)	Energy shortage (%)	Peak shortage (%)
1990 – 91	7.87	15.53	-*	-*
1991 – 92	7.80	18.79	-*	-*
1992 – 93	8.33	20.49	-*	-*
1993 – 94	7.35	18.31	-*	-*
1994 – 95	7.09	16.45	-*	-*
1995 – 96	9.15	18.28	-*	-*
1996 – 97	11.51	17.97	-*	-*
1997 – 98	8.60	11.20	-*	-*
1998 – 99	5.90	13.9	11.80	12.80
1999 – 00	6.20	12.40	7.90	12.50
2000 – 01	7.80	12.30	7.60	15.30
2001 – 02	7.50	11.80	7.10	13.10
2002 – 03	8.80	12.20	6.00	4.40
2003 – 04	7.10	11.2	1.40	3.00
2004 – 05	7.30	11.70	0.60	0.50
2005 – 06	8.40	12.30	0.60	2.30
2006 – 07	9.60	13.80	1.80	2.40
2007 – 08	9.90	16.60	2.90	11.7
2008 – 09	11.10	11.86	7.85	6.09
2009 – 10	10.10	12.70	6.19	7.47
2010 – 11	8.50	10.30	6.45	7.10
2011 – 12	10.30	12.90	10.65	7.22

-* Data not available

To improve the energy generation, TANGEDCO has proposed and executed many thermal schemes such as Mettur stage – II, North Chennai – II, etc. At the same time, it is required that all the existing power plants need to operate at the maximum possible extent. For peak management, Tamil Nadu grid mainly depends on conventional hydro stations, Kadamparai pumped storage and few Gas power stations. Even though all these peak power plants are operated to the maximum possible extent, shortage of peak power exists. The measures for improved output from Kadamparai pumped storage plant have also been tried by the authorities similar to the above mentioned plants.

In this context, this research work is aimed at improving the performance of the Kadamparai pumped storage plant by adopting certain reservoir regulation and by introduction of variable speed machines during renovation and modernization since the station has served for more than 26 years.

3.10. PROBLEMS ASSESSED

A critical review of the historical record of the plant operation shows that has been designed for the annual energy production of 797 MU (as per DPR), it has not been achieved so far and a maximum of 73% of that has been only achieved. The reasons for the same are attributed to the following causes:

- Less pumping operation than envisaged in the DPR.
- Waste of water through spillage.

The above two parameters have been analyzed in detail in the following chapters.

3.10.1. Less pumping operation

For Kadamparai pumped storage plant as per design, 8 hours pumping and 6 hours generation was projected in the DPR. But due to the reasons mentioned in the section 3.6, the plant did not get the sufficient input power for pumping from thermal/nuclear stations. Hence poor performance or less performance was experienced from 1986 to 2000. However, due to the more wind installations of the state from 2001 onwards, the pumping status is found increased. For checking the pumping status of the plant, one month pumping and generation pattern has been studied and is shown in the Annexure - 3. March 2009 has been considered being summer month, with less inflow to the reservoirs and also due to high demand. The pattern clearly shows the pumping gap and if the gap is bridged, then the generation would be increased consequently. But the pumping always depends on the grid surplus, which is always deficit. At the same time, the authorities have observed from the load curve pattern of the state that there is a surplus power availability in the grid little below the threshold i.e. 70 to 100 MW for certain duration and some machines have been back down their generation. If such a condition persists, for e.g. 90 MW, then one pump of capacity of 110 MW as synchronous machine can be operated with 90 MW capacity on part load.

3.10.2. Spill analysis

The objective is also to study the spilling occurring from Upper Aliyar (UA) reservoir especially during high monsoon period and its possible utilization. In hydropower production, mainly water is discharged through the turbines for power generation. The water passed above the full reservoir level is considered as spill and the energy from the spill water cannot be utilized. Minimizing the spill from the reservoirs would maximize the power generation. Regarding Kadamparai reservoirs, the following quantity of the spill has been experienced from the year 1998 – 2010 which is given in the Table 3.2. The total quantity of spill from 1998 to 2010 is 9528.84 Mcft. If this quantity of water is discharged through the Kadamparai turbines, it can produce additional 238 MU of energy. Utilization of this total quantity of discharge through the upper Aliyar power house (UAPH) turbine is not possible since it has a limited capacity of 50 Mcft discharge per day. But there is a possibility to utilize a portion of spill water efficiently, if the reservoirs are regulated effectively. Such a reservoir regulation can also improve the plant performance of Aliyar power house to a considerable level. The above mentioned operating regime has been studied in detail in this thesis and analysis and conclusions have been presented in Chapter - 4.

Table 3.2 Spill & inflow details for the period of 1998 – 2010

Year	Natural inflow (Mcft)	No of days spill occurred							Quantity of the spill (Mcft)
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1998-99	6094	-	-	-	1	5	4	2	658.72
1999-00	4887	-	-	-	2	-	-	-	134.00
2000-01	4697	-	-	7	1	-	-	-	1129.00
2001-02	3826	No spill							0
2002-03	3039	No spill							0
2003-04	2495	No spill							0
2004-05	3114	7	9	2	-	-	-	-	1119.73
2005-06	6916	-	4	6	10	5	8	-	2284.42
2006-07	4467	-	-	-	-	1	-	-	2.52
2007-08	6114		15	13	8	7	-	-	2638.93
2008-09	3788	-	-	2	-	-	-	-	83.52
2009-10	4693	-	10	4	1	3	-	-	1478.00

3.11. PROPOSED REMEDIAL MEASURES TO IMPROVE THE PLANT PERFORMANCE

With the above operation and performance analysis and keeping the view of above assessed problems, the following two methods have been proposed to improve Kadamparai pumped storage plant's performance.

- Reservoir regulation
- Use of variable speed drives instead of existing fixed speed drives during renovation and modernization of the power station.

The above two remedial measures have been analyzed in the following chapters 4 and 5.

Chapter 4
RESERVOIR REGULATION FOR KADAMPARAI PUMPED STORAGE PLANT

4.1. INTRODUCTION

The analysis carried out in this chapter describes the determination of water regulation for Kadamparai and Upper Aliyar power house to improve the overall performance of the pumped storage scheme. The background of this analysis is based on the justifications and objectives mentioned in Chapter - 3. Spill recorded from the lower reservoir is the great concern and the possible reduction in spill will improve the performance of the plant. The discharge capacity of the Upper Aliyar power house (1x60 MW) is of 2.15 Mcft per hour and is the major reason for the spill is more release from upper reservoir during high inflow period. Higher storage maintained during poor monsoon period in the lower reservoir creates a situation caused spill if followed by a high monsoon year. Further, spill is noticed while operating the station during emergencies of the state grid with a higher storage i.e. very near to the full reservoir level, at the lower reservoir. Certain storage has to be maintained throughout the year in both the reservoirs for reliable operation and such storage maintained is analyzed for improving the operating performance of the station.

Considering all the operating constraints as narrated above, operating rule curves have been derived. The major objectives for this analysis are

- To maximize the plant performance for the reasons mentioned in the previous Chapter - 3.
- To minimize the spill of the lower reservoir to the extent possible especially during monsoon periods by releasing the discharge in advance from the lower reservoir and to keep acceptable storage for all seasonal operation.
- To derive reservoir rule curves since there is no such standard rule curves available for the operation of the plant.
- To frame expert guidance to operate the plant efficiently as suggested by Central Electricity Regulatory Commission (CERC), Government of India guidelines.

A water regulation model has been developed based on hydrological mass balance for obtaining the above objectives and has been applied to Kadamparai pumped storage plant to evaluate its performance. Based on historical operation pattern, expert opinion and simulation results, monthly reservoir storage curve and operating policies have been derived with minimized spill and maximized energy output.

The analysis mainly focuses on effective reservoir regulation on real time measure as other factors associated with a mixed flow pumped storage operation in the deficient southern regional power system, which is complex in nature and not yet analyzed so far. Further, CERC, Government of India, in its regulations for efficient use of pumped storage operation [31], insist to utilize the excess natural flow of the reservoirs, which spill during the monsoon season and advised to run the plant as “must run” basis to avoid the spill and make use of the spill as utilizable energy. Hence, a simulation model has been developed to derive effective operating policies for a Kadamparai pumped storage scheme with the constraints of maximizing the energy generation and minimizing the spill.

4.2. PRESENT ANALYSIS

The Kadamparai reservoir acts as upper dam of the PSP having four reversible pump turbine units. The combined gross capacity of both the reservoirs i.e. Kadamparai & Upper Aliyar is around 2 TMC (Thousand Mcft). But the utilizable storage limit is 1.5 TMC approximately. The remaining 0.5 TMC is the dead storage and could not be used during pumping operations. Available natural inflow from the catchment of the both reservoirs makes this PSP as a mixed PSP.

The designed generation capacity of KPSP is 797 MU annually as per DPR with the condition of 6 hours generation and 8 hours pumping daily, which includes 77 MU that could be generated from natural flow. Even though the KPSP is performing well among all other commissioned PSPs in the country, it has not reached the target generation as per DPR. The records of the power generation show that the maximum generation achieved by the plant was 581.45 MU in the year 2005 - 06. It clearly indicates the possibilities of the increasing the power generation nearer to DPR capacity by effectively reducing the spill and to do more recycling of water. The present analysis aims to maximize the plant performance, minimize the spill at UA dam and convert it as utilizable energy. Whenever heavy inflow received by both the reservoirs during monsoon period, effective use of the water for power generation is possible at upper dam through Kadamparai machines, whereas the release from Kadamparai machine plus natural inflow develops quick storage increase in the lower reservoir and because of low discharge capacity i.e. 50 Mcft/day of Aliyar machine spill was noticed mainly at upper Aliyar reservoir during monsoon times.

In the present analysis, a water regulation model has been developed by the method of simulation to identify the power generation gap of the system. The power generation gap is filled by maximizing the discharge of the power plants. This is done by different combinations of additional discharge of both the power plants within the frame work of system. Generally, the hydropower plants are operated with a well formulated rule curves. But the operation of the pumped storage always depends on the grid conditions. The results of this analysis will also bring out certain guidelines for storage and discharge of the system to perform better with minimum spill. At the same time, this study will also suggest expert ideas to operate the reservoirs based on the knowledge of natural inflow, grid conditions and historical plant operating experience.

4.3. MODEL DESCRIPTION

In general, the operation of pure pumped storage plant always depends on the grid conditions. Whereas in the case of mixed PSPs, the operation not only depends on the grid condition, it depends on the natural flow conditions also. The KPSP is also operated for longer duration on generation mode during monsoon time since it receives sufficient amount of inflow from rainfall. The catchment of KPSP faces two seasons viz summer and winter. The winter season receives rainfall from two monsoons namely south-west (June to September) and north-east (October to December). The KPSP system receives maximum inflow during the winter season and faces spill during this period. The inflow received during the winter season has to be stored and used to operate the plant during summer months also. The KPSP has been designed to operate daily, weekly and monthly schedules. However, the water regulation of the reservoirs has to be accounted throughout the year. Under these circumstances, the simulation of the performance of the reservoirs for few days, weeks and months will not give any suggestions for practical operation. So it has been decided to simulate the plant performance at least for few years. Based on the availability, 5 years of historical data from 2006 to 2010 have been selected for analyzing the plant performance. Keeping in view of the above, a water regulation model (Annexure – 4) has been developed to simulate the water regulation process of KPSP.

All the components of mass balance of the upper reservoir and lower reservoir have been modeled in the spread sheet. The mass balance of upper reservoir includes initial reservoir storage, natural inflow from the catchment, pump inflow from the lower reservoir, and discharge from the reservoir for power generation and spill. The mass balance of lower reservoir includes initial reservoir storage, natural inflow from the catchment, discharge for the power generation, spill from the upper reservoir, pump outflow from the lower reservoir and spill. All these components are interlinked together by the cell formulation in the worksheet. For example the entry of pump out flow from the lower reservoir is automatically passed to the upper reservoir storage. Thus the pure practical operation of KPSP has been modeled. One small hydro power plant (SHP) 'Poonachi' is also located in the KPSP hydro chain. The discharge of Poonachi SHP is naturally carried into UA reservoir. The quantity of flow and duration of operation of the plant are insignificant and the same are not considered in the development of the model. The mathematical formulation of mass balance of the reservoirs is given as follows:

4.4. MODEL FORMULATION

Mass balance for reservoir 1 (Kadamparai Reservoir),

$$S1_{t+1} = S1_t + IL1_t + IP_t - Q1_t - SP1_t \tag{1}$$

Mass balance reservoir 2 (Upper Aliyar Reservoir)

$$S2_{t+1} = S2_t + IL2_t + SP1_t + Q1_t - IP_t - Q2_t - SP2_t \tag{2}$$

Where,

$S1_t$ = storage of the upper reservoir at time *t*

$S1_{t+1}$ = storage of the upper reservoir at time *t+1*

$S2_t$ = storage of the lower reservoir at time *t*

$S2_{t+1}$ = storage of the lower reservoir at time *t+1*

$IL1_t$=Local inflow from the catchment of upper reservoir at time *t*

$IL2_t$=Local inflow from the catchment of lower reservoir at time *t*

$Q1_t$=Discharge from the upper reservoir for power generation at *t*

$Q2_t$=Discharge from the lower reservoir for power generation at *t*

$SP1_t$=Spill from upper reservoir at time *t*

$SP2_t$=Spill from lower reservoir at time *t*

IP_t=Pump inflow from lower reservoir at time *t*

Constraints

4.4.1. Storage constraints

$S1_{min} \leq S1_t \leq S1_{max}$ for upper reservoir (3)

Where,

$S1_{min}$= minimum storage of upper reservoir i.e., 150 Mcft

$S1_{max}$= maximum storage of upper reservoir i.e., 1080 Mcft

$S2_{min} \leq S2_t \leq S2_{max}$ for lower reservoir (4)

Where,

$S2_{min}$= minimum storage of lower reservoir i.e., 250 Mcft

$S2_{max}$= maximum storage of lower reservoir i.e., 980 Mcft

4.4.2. Power house generator discharge constraints

$Q1_t \leq 384\ mcft$ Maximum discharge from the upper reservoir for power generation for t where t=24 hours

i.e. 4units X 4 Mcft X 24 hours = 384 Mcft (5)

$Q2_t \leq 51.6\ mcft$ Maximum discharge from the lower reservoir for power generation for t where t = 24 hours

i.e. 1unit X 2.15 Mcft X 24 hours = 51.6 Mcft (6)

4.4.3. Pumping discharge constraint

$IP_t \leq 288\ mcft$ Maximum pump inflow from lower reservoir for t, where t=24 hours

i.e. 4 units X 3 Mcft X 24 hours = 288 Mcft (7)

IP_t=Maximum pump inflow from lower reservoir for t, where t=24 hours

Simulation of the reservoirs has been done by following the mass balance equations (1) & (2) with storage, discharge and pumping discharge constraints (3) to (7) with various combinations of storage and discharge of the reservoirs to achieve minimum spill from the lower reservoir and thus to increase the power generation from the pumped storage scheme. The mass balance of the system is represented by Figure 4.1.

4.5. SIMULATION OF THE RESERVOIRS

Normal practice adopted by TANGEDCO for operating the cascaded reservoirs is to store maximum water during rainy period and to reach FRL anticipating the monsoon failures and then utilize the inflow according to grid demand and to avoid spill of water to the extent possible. The full storage is to be used up to May of every year taking into account of other factors of grid management. The inflow from upstream reservoir is released to the downstream reservoir or for irrigation according to PWD demand for the dams under their control. Once upstream reservoir level is reached to FRL, water is released either through generation or through spill discharge for irrigation. Since both Kadamparai and upper Aliyar are TANGEDCO dams, PWD is insisting water release for irrigation only during monsoon failure times. Normal operation of upper Aliyar proves its adequacy for irrigation release. However, the lower Aliyar is having a storage capacity of 4000 Mcft. It is accommodating the release from upper Aliyar through generation and as well as by opening surplus gate. It could be observed from the table 1 that the spill is more during July to October at upper Aliyar dam and mainly due to monsoon inflow. Other causes of spill are meagre when compared with monsoon inflow. TANGEDCO practice emphasizes the combined storage of KPSP as 2000 Mcft at the end of monsoon period and to effectively meet the summer demand for the flexible operation almost throughout the year. The spill from UA reservoir is observed by operating the reservoirs from these existing practices. The simulation of operation of the reservoirs has been done with existing practice and the combined storage is limited to 1600 Mcft as initial condition for July to December since spill occur during this period only.

In general, increase in existing discharge from reservoirs reduces the spill and increases the generation if the condition permits. This change in discharge may reflect on combined storage of the system. The present simulation study of the reservoirs derives a new rule curve which reduces or nullifies the spill by maximizing the present discharge pattern. At the same time, the effect of the change in combined storage on the system performance has also been analyzed.

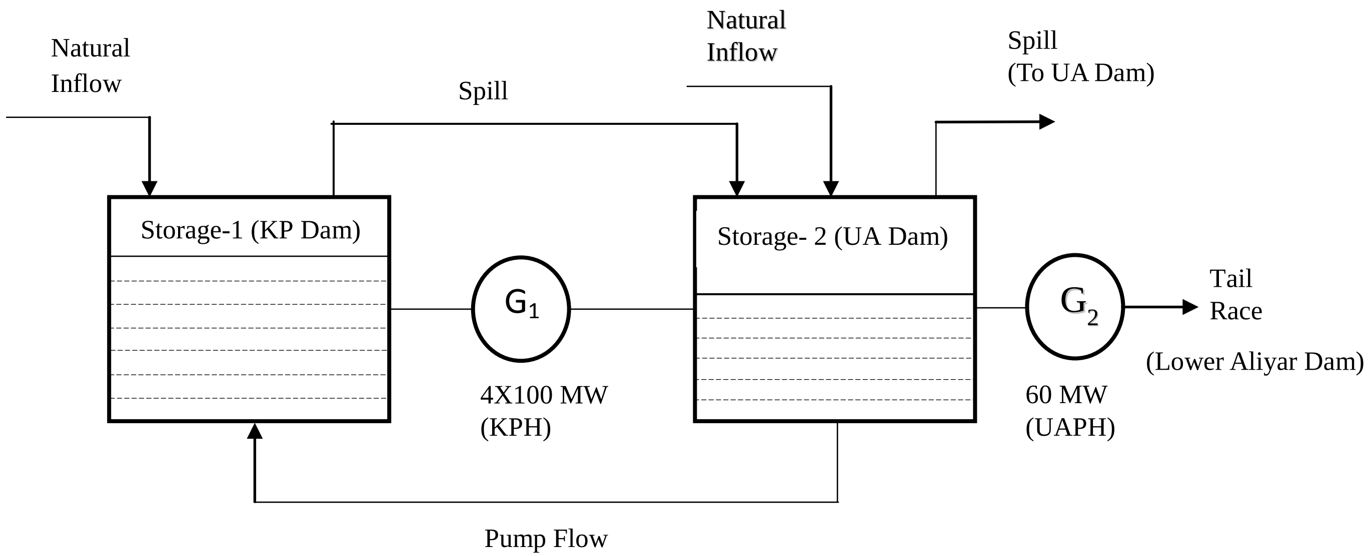


Figure 4.1 Schematic diagram for mass balance of the system

Table 4.1 Various combinations tried for simulation

Kadamparai	Upper Aliyar	Remarks
8 Mcft	-	Reduced Combined storage & spill occurred at UA
4 Mcft	-	Spill occurred at UA
4 Mcft	**3 Mcft**	**Found suitable**
2 Mcft	3 Mcft	More generation gap identified

For achieving the above mentioned objectives, different combinations of discharge patterns for upper and lower reservoirs have been tried (refer table 4.1). Finally two methods have been adopted in this simulation: one is 4/3 check and the other is maximizing the UA reservoir discharge only. In the 4/3 check, two numerical variables (4 and 3) have been selected for varying the discharge from upper and lower reservoirs of KPSP, i.e. adding 1 generating unit or one hour additional generation for every day's discharge in both the reservoirs. The operation of one generation unit of KPH will replace 4Mcft of water for one hour from the reservoir and UAPH generator will replace 2.15 Mcft of the water for one hour, which is rounded to 3 Mcft for simulation flexibility. By analyzing the past operational data, it has been observed that the maximum discharge per day from KPH was around 250 Mcft. The maximum discharge could be 384 Mcft if it is operated for 24 hours continuously. Since pumping is to be done regularly which will be normally between 10:00 PM and 5:00 AM, for calculation purpose, the generator operation hour is limited to 16 hours during high inflow period. It may be increased if FRL is maintained at upper dam and further inflow is continuing where there is no margin/space is available for pumping. In such occasion, 24 hours generation is possible to accommodate inflow for power generation. So there is a possibility of increasing the operational duration of the plant for one hour in all the days of a month and the same is considered in the simulation analysis. The UAPH is operated to its maximum capacity in some days since it has only one generating unit. It is not possible to increase the discharge by 3 Mcft in all the days. So it is decided to increase the discharge of the plant by 3 Mcft whenever the discharge is less than or equal to 47 Mcft. During the high inflow periods, the 4/3 check method cannot be applied since it experiences the spill. In this kind of situations, the second simulation has been adopted i.e., maximizing the UAPH discharge to reduce the spill to the possible extent. The above mentioned simulation methods have been carried with existing pumping pattern of PSP. The pump is a synchronous machine, pumping is possible only when the frequency band is in between 49.5 to 50.5 Hz which always depends up on the grid. The simulation is adopted to check the possibility of increasing the output from Kadamparai and Aliyar without increasing the pump discharge. But for pumping, we need surplus power input between 110 MW and 440 MW which could not be created for simulation purpose as a standard practice since all the southern states are facing short in generation, and demand is ever increasing and pump operation is based on day to day condition of the grid, hence changes are made in the study whenever spill is noticed in 4/3 check method.

4.6. ANALYSIS OF SIMULATION RESULTS

The two methods such as 4/3 check method and maximizing the discharge of UAPH only have been applied in the simulation analysis of the reservoirs for the years from 2006 to 2010 for the months of July to December.

4.6.1. Simulation results for the year 2006

TANGEDCO classifies the inflow into Kadamparai system in three categories viz. the inflow above 5000 Mcft is high inflow year, 4000 to 5000 Mcft is normal inflow year and below 4000 Mcft is low inflow year. The annual inflow to Kadamparai reservoir during 2006 was 4733 Mcft which was a normal inflow as per the classification of TANGEDCO. The power generation was 427.81 MU. The water pumped in this year was 11469 Mcft. This year was recorded as no spill year. Even though it was a no spill year, a spill of 2.54 Mcft was observed from UA reservoir on 14th October which was occurred due to the high discharge of 88.51 Mcft from upper reservoir to meet out the peak power requirement of the grid. The spill of 2.54 Mcft for this year is negligible and it is also operational spill. However, simulation has been carried out for the winter season of 2006 to explore the possibilities of increase in power generation with existing operational pattern of the system. The combined storage of the reservoirs and the energy generated (sample calculation is shown in Annexure – 5) before and after simulation are presented in the following Figures 4.2 and 4.3.

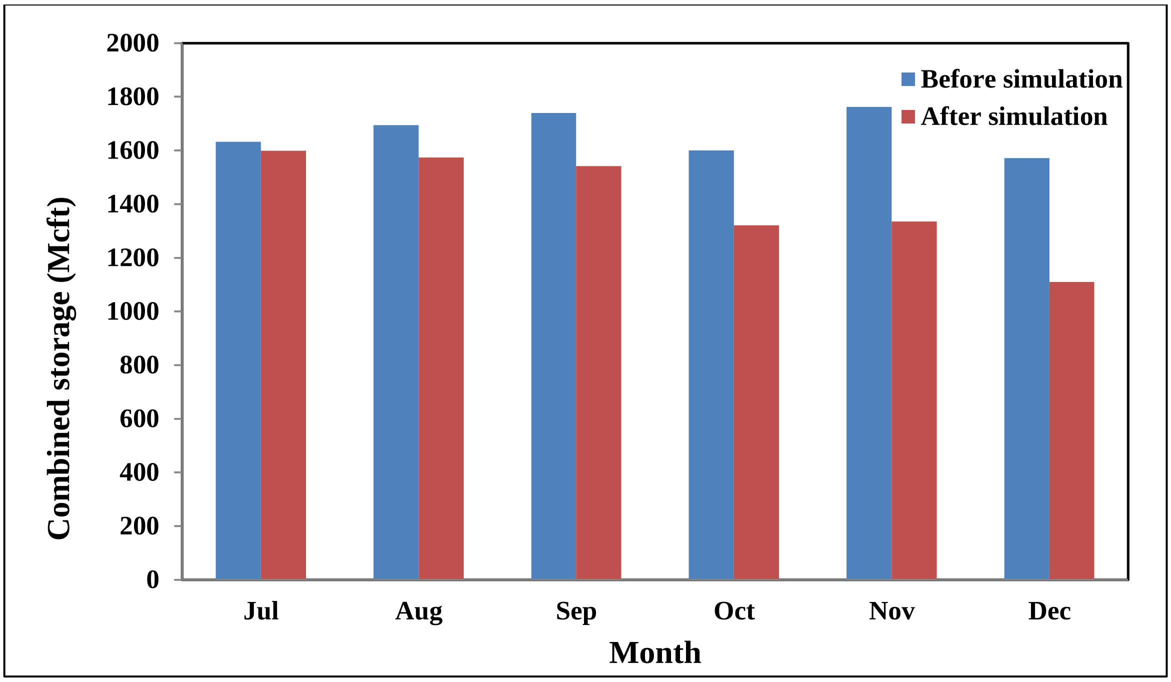


Figure 4.2 Combined storage pattern for the winter of 2006

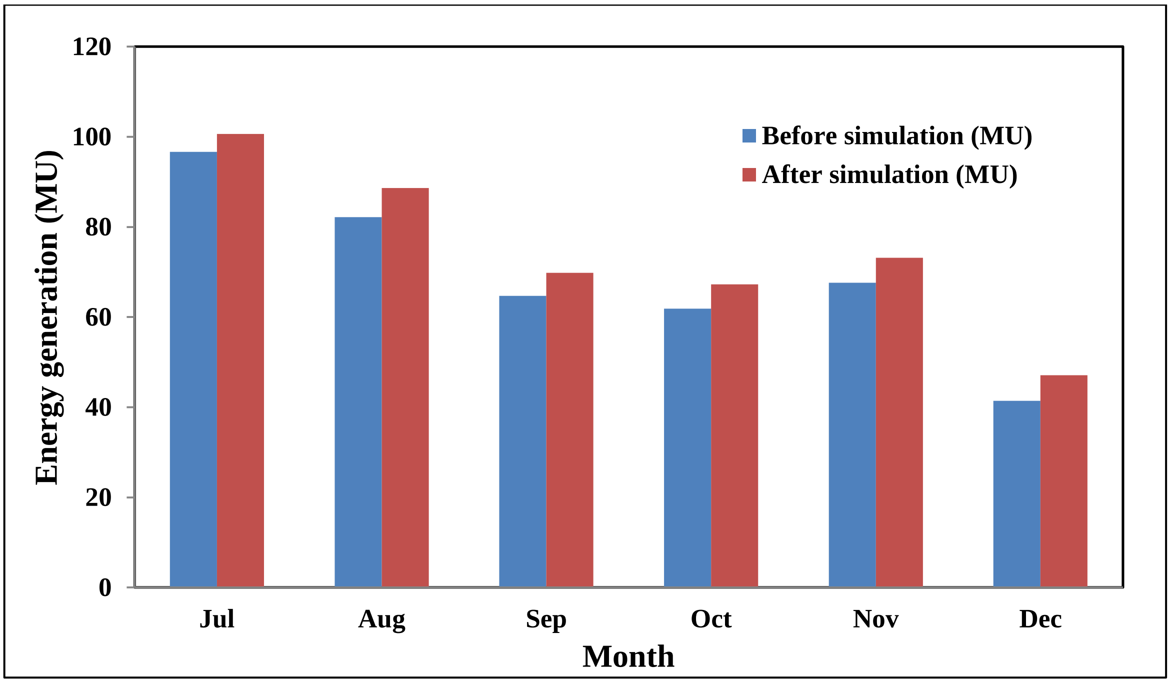


Figure 4.3 Energy generation for the winter of 2006

An additional energy of 32.12 MU could be generated by adopting 4/3 check method in the simulation analysis. Considerable quantities of spill have been observed for the months of July, August and October. For avoiding such spills and operational flexibility of the system 155 Mcft of water has been pumped during the week ends of the above months. The regulation of the reservoirs for the next season i.e., 2007 summer has been checked after the simulation. It reveals that the combined storage reduces below 100

Mcft from 5th April onwards. Further, the storage reaches below zero from 27th April and it recoups above the zero from 23 June onwards. It indicates that release pattern by 4/3 check method could not be suggested as it affects the future operation of the plant.

4.6.2. Simulation results for the year 2007

The annual inflow during 2007 to Kadamparai reservoir was 5933 Mcft and it was a high inflow as per the classification of TANGEDCO. The power generation was 456.58 MU. The water pumped in this year was 9004 Mcft. The system experienced high spill of 2639 Mcft, which was highest during the last 13 years. The operation of the KPSP was suspended from 28th May to 30th June for maintenance works. The operation of UAPH was also suspended from 6th June to 25th June for annual over haul. However, the reservoir storages of Kadamparai and UA reservoir were maintained at a minimum of 246.27 Mcft and 440.82 Mcft for the future operation of the system. The monsoon was set in from 16th June onwards and gradual inflow was received till 2nd July. A notable inflow of 223.24 Mcft was observed at Kadamparai reservoir on 22nd June. Due to this vigorous monsoon, the reservoir spilled 290 Mcft from 1st to 4th July. During the same period UA reservoir also received considerable inflow at regular interval. An inflow of 169.92 Mcft was observed on 13th June. For utilizing this high inflow, the Kadamparai power house was brought into operation from 2nd July onwards. The storage of UA Reservoir reached FRL due to the continuous operation of the Kadamparai power house and it caused spill. All above mentioned circumstances lead to spill of 1021Mcft and 837 Mcft during the months of July and August. The continuous monsoon and grid conditions forced the system to experience the spill of 462 and 320 Mcft during the months of September and October. The Kadamparai reservoir experienced no spill except 4 days of July due to the high unit discharge capacities whereas UA reservoir experienced continuous spill during this period since it is equipped with single power generating unit. To check adequacy of the reservoirs for regulating the inflow, operation has been simulated by maximizing the UAPH discharge method for the period of July to September. The results of the simulation are presented in the following Figures 4.4 and 4.5.

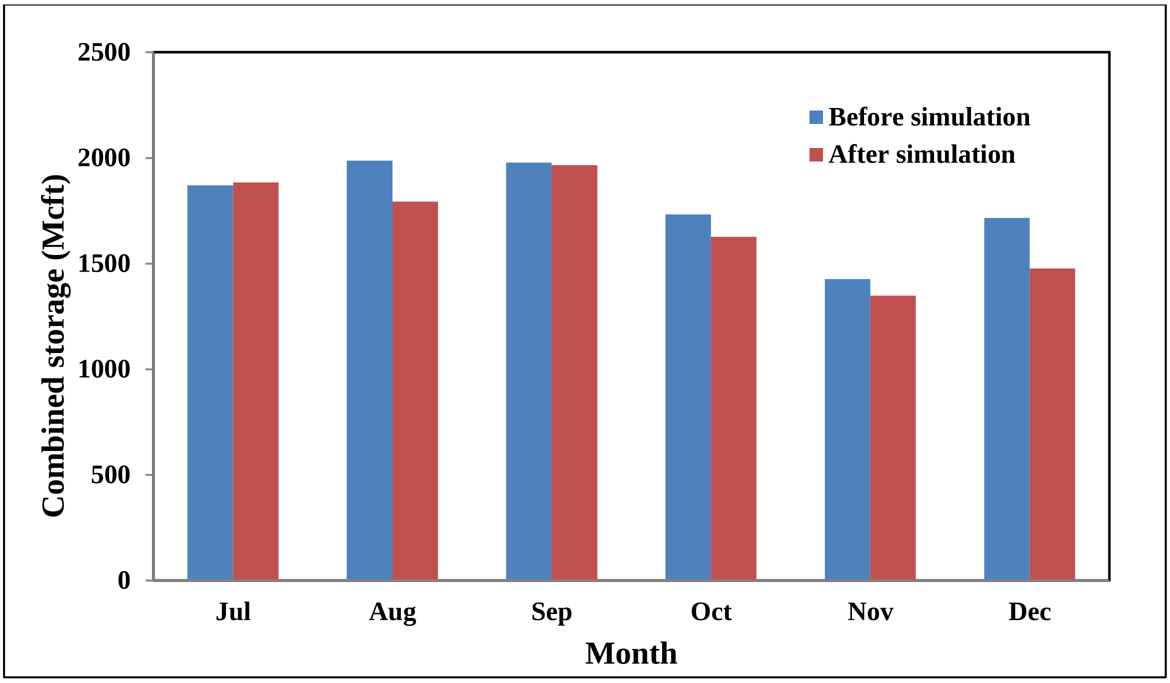


Figure 4.4 Combined storage pattern for the winter of 2007

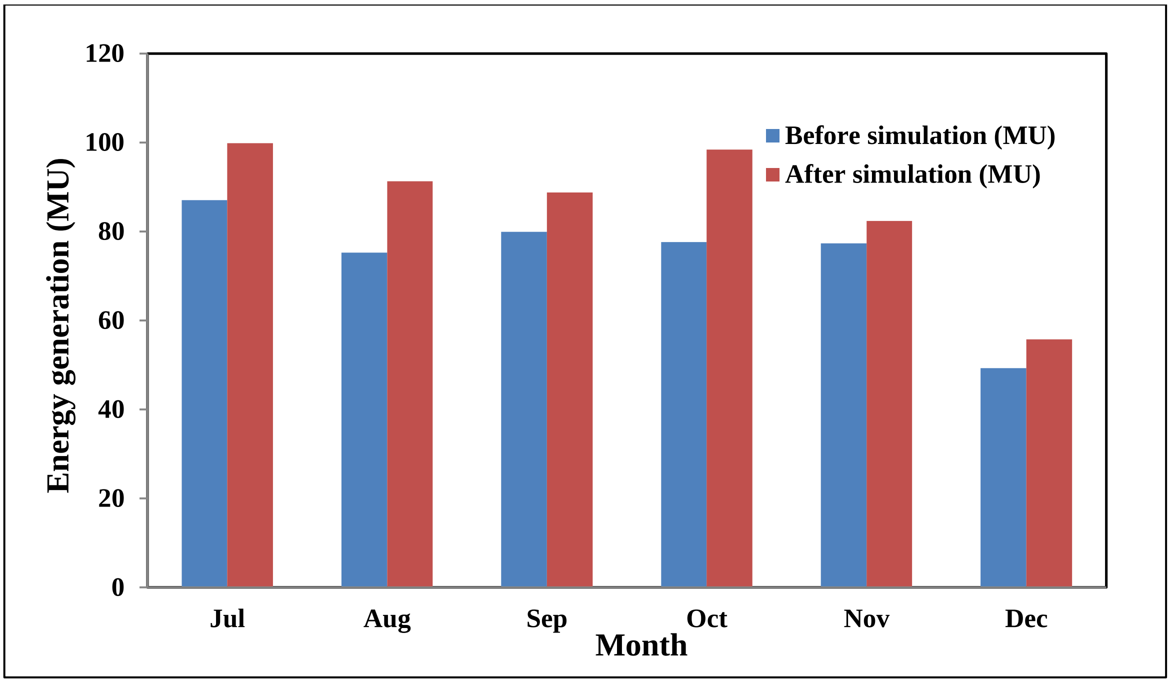


Figure 4.5 Energy generation for the winter of 2007

The mass balance of the model for this year has been done by taking the data of 2010 from 28th May to 30th June for Kadamparai reservoir and from 6th June to 25th June for UA reservoir since the operation of the plants was suspended during these periods. The imposing of the data of 2010 induces spill (approximately 800 Mcft) from UA reservoir. However, the simulation by maximizing the UAPH discharge method reduces these spills considerably. Further same simulation method has been adopted for the months of August, September and October also. No spill is observed for the months of September and October. A considerable amount of spill is reduced during the month of August. The simulation of reservoir operation for months of November and December has been done by 4/3 check method. The results of the simulation for December reveal that a negligible amount of spill is observed and it could be avoidable by practical operation. An additional energy of 70.14 MU has gained from the simulation analysis.

The simulation of the year 2007 divulges the following observations:

- Uncertainty in predicting the monsoon increases the difficulty of reservoir regulation. However during monsoon period according to the inflow, maximum discharge of UA Reservoir is to be utilized and effective pumping and generation has to be used to balance the reservoir regulation.
- When both the reservoirs reach their maximum even after full discharge of UA, spill occurs. It is natural and beyond control of the reservoir regulation.
- In high monsoon period, operation on allowing less combined storage is recommended since spill would occur if the inflow is high and continuous.
- Once both the reservoirs reach their FRL, the only possible discharge is through UAPH which imposes the restriction of 51.6 Mcft/day. Hence, it is recommended to operate UAPH at the maximum and keep the combined storage to the extent possible for flexible generation and pumping operation of KPSP, for which again it is recommended to keep the combined storage at lesser level.

4.6.3. Simulation results for the year 2008

The annual inflow during 2008 to Kadamparai reservoir was 4018 Mcft and it was a normal inflow as per the classification of TANGEDCO. The power generation was 291.72 MU. The water pumped in this year was 7613 Mcft. The system experienced spill only on two days which amounts to 84 Mcft. Even though the spill is negligible quantity, the simulation has been carried out to check the possibility in improving the performance of the plant. The combined storage for the month of July 2008 is about 727 Mcft. The storage of Kadamparai reservoir is 242 Mcft. The simulations with 4/3 check method leads to the reservoir level below MDDL. So it will not be a practical solution. Hence, the simulation has not been carried for this month. The simulation results for the remaining 5 months August to December 2008 are given in the below Figures 4.6 and 4.7.

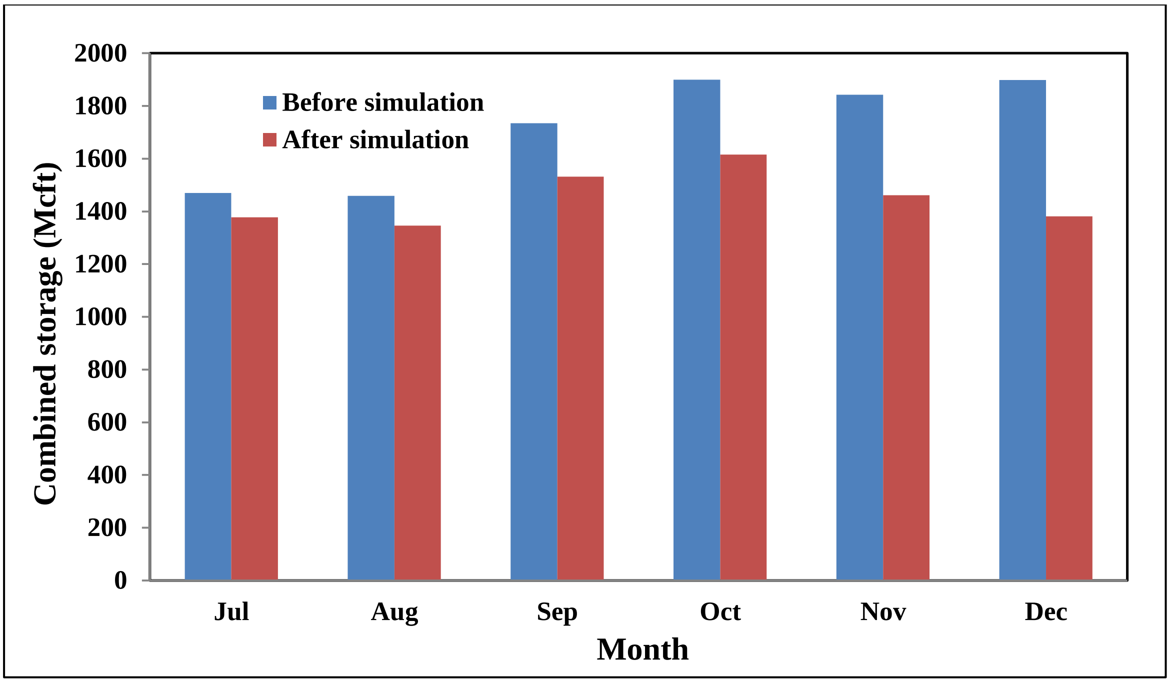


Figure 4.6 Combined storage pattern for the winter of 2008

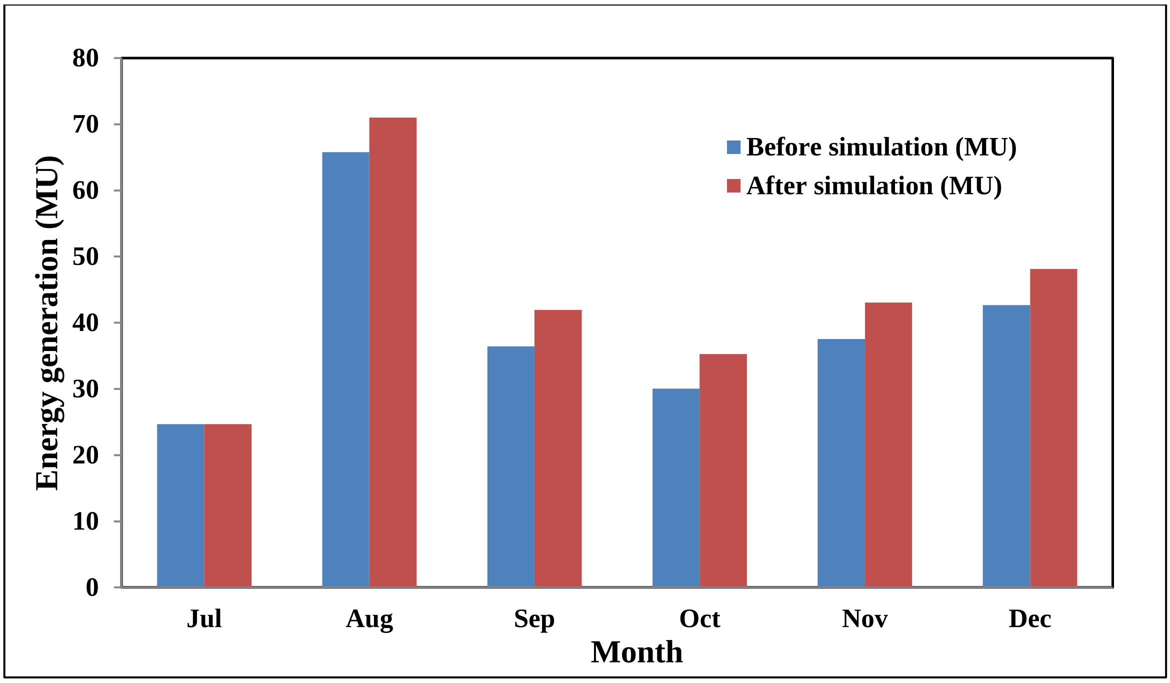


Figure 4.7 Energy generation for the winter of 2008

The 4/3 check method reduced the spill considerably. Only few operational spills have been observed for the months of August, November and December which can be eliminated by practical operation. As per simulation, an amount of 26.96 MU is gained as an additional energy.

4.6.4. Simulation results for the year 2009

The annual inflow during 2009 to Kadamparai reservoir was 4828 Mcft and it was a normal inflow as per the classification of TANGEDCO. The power generation was 98.81 MU. The water pumped in this year was 15080 Mcft. The system experienced spill of 1478 Mcft. The spill in July, August, September and October were 894, 163, 32 and 389 Mcft respectively. The spill in the month of July was due to grid demand and monsoon condition. The spills in other months were due to grid demand only. Under these circumstances, the simulation has been done with only maximizing the UAPH discharge for the months of July, August, September and October since system experienced more spill. The simulation for the remaining two months November and December have been carried by 4/3 check method. The simulation results for the year 2009 are given in the below Figures 4.8 and 4.9.

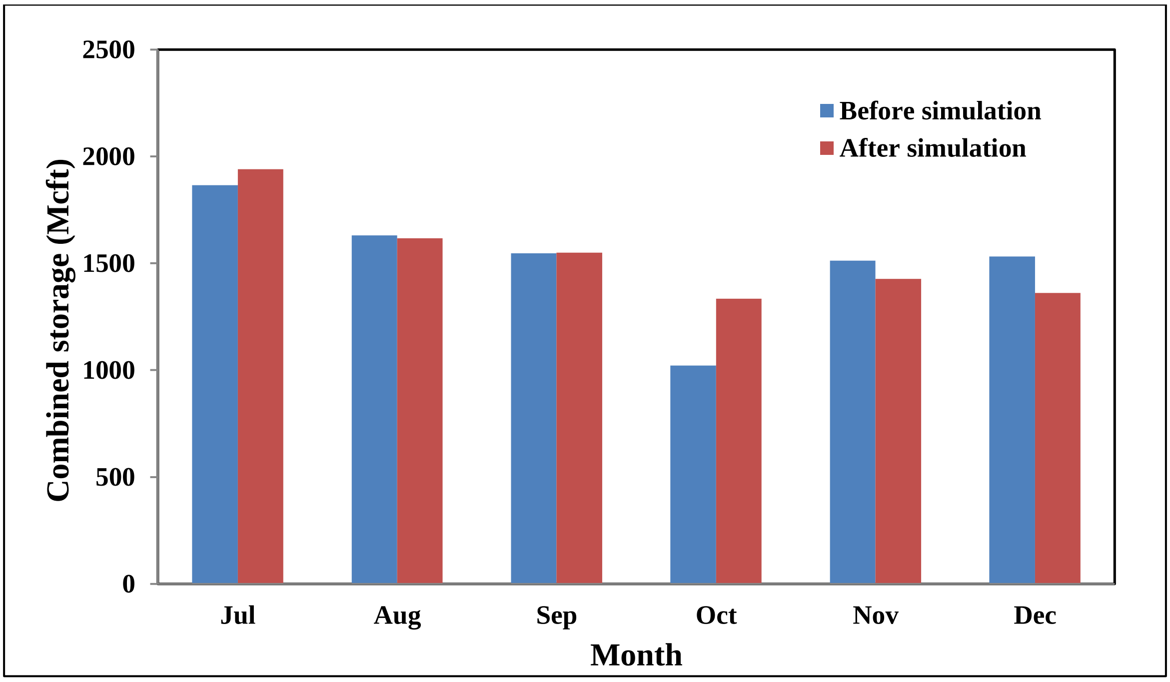


Figure 4.8 Combined storage pattern for the winter of 2009

In the month of July though the combined storage is maintained at 904.77 Mcft, the storage level has been found gradually raised even after allowing maximum discharge of UAPH and a spill has occurred from 19th July since the increased monsoon inflow from 13th July to 20th July made the water level in both the reservoirs to reach the FRL. However, the reservoir storage has been brought back to 850 Mcft (combined storage) by running the power plants. A possible reduction of spill can be achieved by reducing the combined storage by releasing more water during the month of June through UAPH.

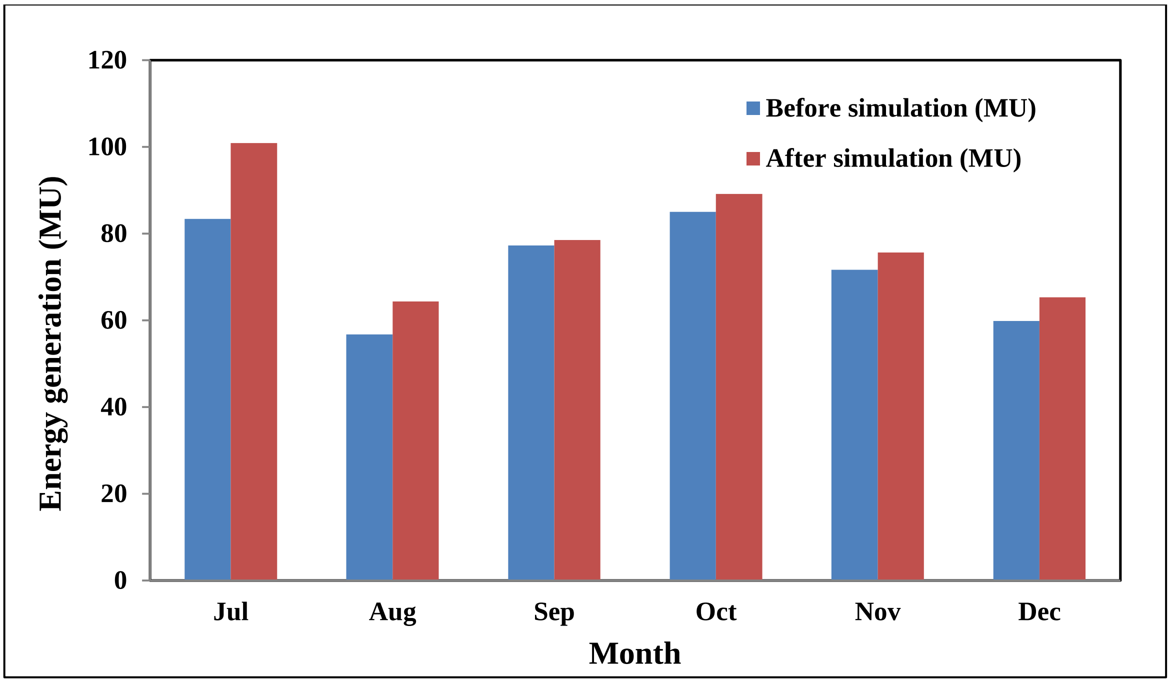


Figure 4.9 Energy generation for the winter of 2009

The simulation with more release during June indicates that the combined storage has been reduced to 815.92Mcft and the spill from 894 Mcft to 323.28 Mcft. The spill for months of August and September has been nullified by operating UAPH to the maximum extent and regulating the pumping and generation of the system. The spill has been observed in the month of October after the simulation but it may be avoided by practical operation of the power plants. But the months of November and December 4/3 simulation method has been adopted and found no spill.

4.6.5. Simulation results for the year 2010

The annual inflow during 2010 to Kadamparai reservoir was 3740 Mcft and it was a poor inflow as per the classification of TANGEDCO. The power generation was 572 MU. The water pumped in this year was 13447 Mcft. The system experienced no spill in this year. However, the simulation has been done to check the possibility of gaining power generation. The 4/3 simulation method has been adopted for all the months of winter season. The simulation results for the year 2010 are given in the below Figures 4.10 and 4.11.

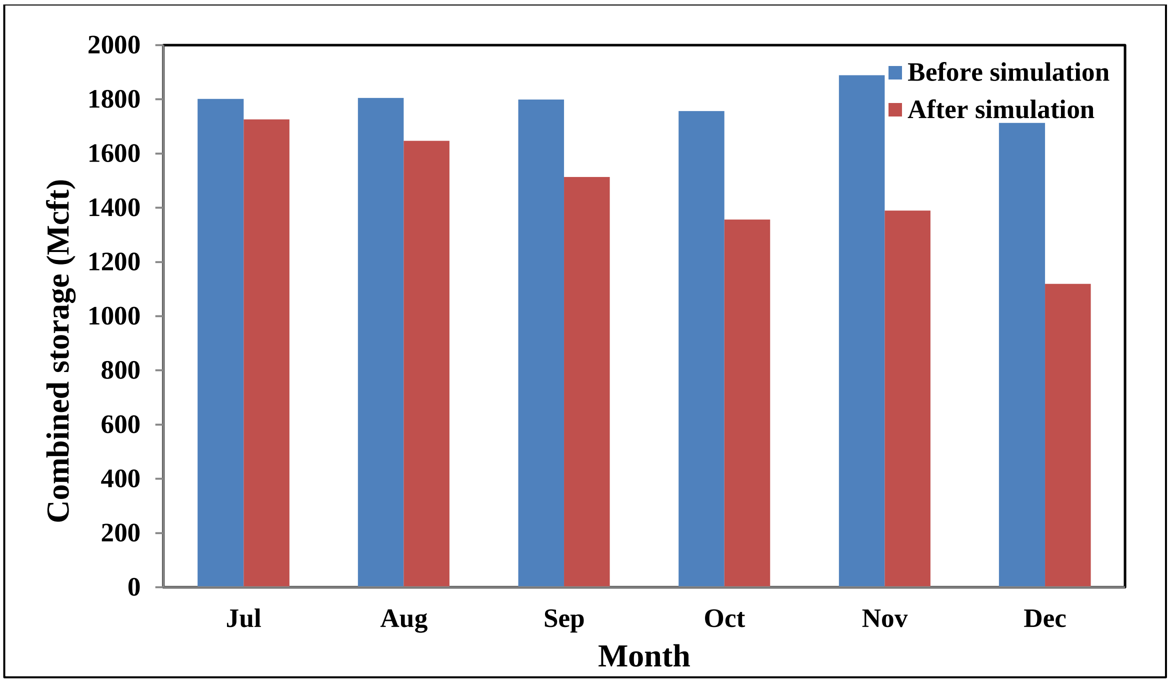


Figure 4.10 Combined storage pattern for the winter of 2010

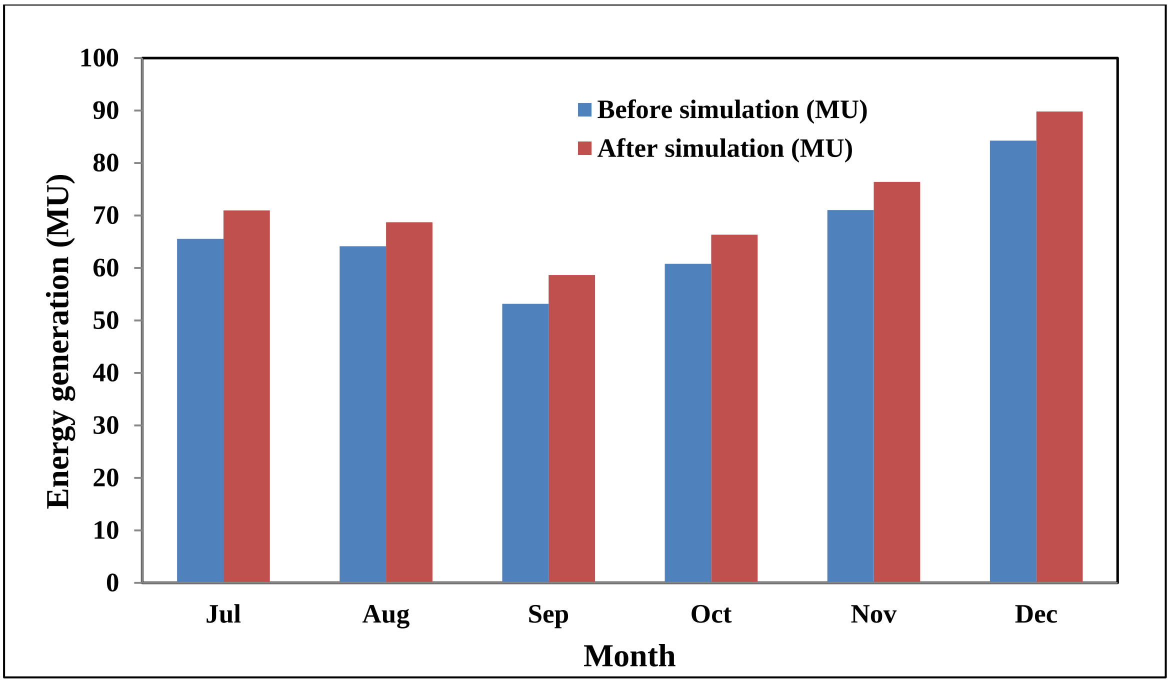


Figure 4.11 Energy generation for the winter of 2010

The simulation results indicate that no spill has been found in the month of July. During the month of August, UAPH has utilized its maximum capacity to meet the higher grid demand (Load shedding imposed from the year 2008 in the state). In this context, adding 3 Mcft with UA discharge is possible for only few days. So the simulation for this month results spill for only three days. These spills may not occur in practical operation.

Similarly, the remaining months of the winter season also indicate 2 to 3 days spill in every month for the above reason.

4.7. INFLOW ANALYSIS

The analysis of Inflow from year 1998 to 2010 clearly indicates that KPSP experienced normal inflow in most of the years as per TANGEDCO classification. The inflow is more during the month of July in comparison to the other months. This following Table 4.2 accounts the number of days in a month when the inflow is more than 50 Mcft and also mentions whether the particular month experienced spill or not. Whenever heavy monsoon set-in, the inflow was accommodated to the maximum storage capacity of both the reservoirs and rest of the inflow was allowed as spill. The maximum one day inflow during this period was approximately 200 Mcft.

Table 4.2 Spill of the days above 50 Mcft inflow

Year	Month	No. of Days above 50 Mcft inflow	Spill
2006	June	5	NS
	July	7	NS
	August	4	NS
2007	June	5	NS
	July	12	S
	August	7	S
	September	6	S
	October	4	S
	December	2	NS
2008	July	7	NS
	August	4	S
	September	4	NS
	October	1	NS
	November	1	NS
2009	June	1	NS
	July	15	S
	September	4	S
	October	4	S
	November	2	NS
2010	June	2	NS
	July	7	NS

NS - No Spill ; S – Spill

Further, the total weekly inflow i.e. inflow to the Kadamparai reservoir and inflow to the Upper Aliyar reservoir has been analysed with the discharge of Upper Aliyar. In other words, the total inflow to the pumped storage system and the outflow from the pumped storage system for the period of five years 2006 – 2010 has been analysed. The mean, standard deviation and the ratio of weekly inflow and outflow (refer Table 4.3 and 4.4) for the above period have been considered for this analysis. The following Figures

4.12, 4.13, 4.14, 4.15 and 4.16 are shown the nature of inflow and outflow of the pumped storage scheme.

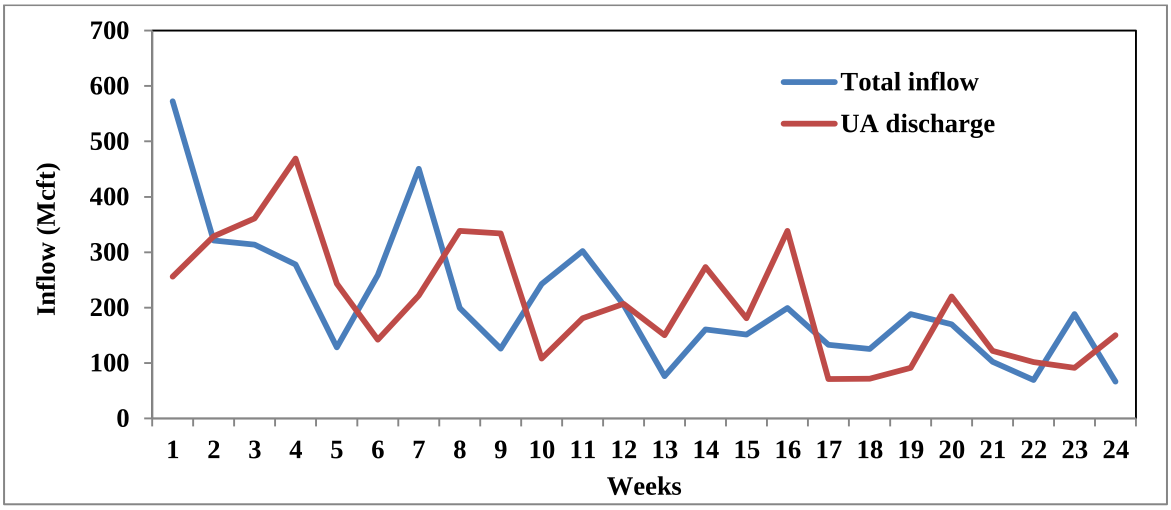


Figure 4.12 Plot for inflow versus outflow (2006)

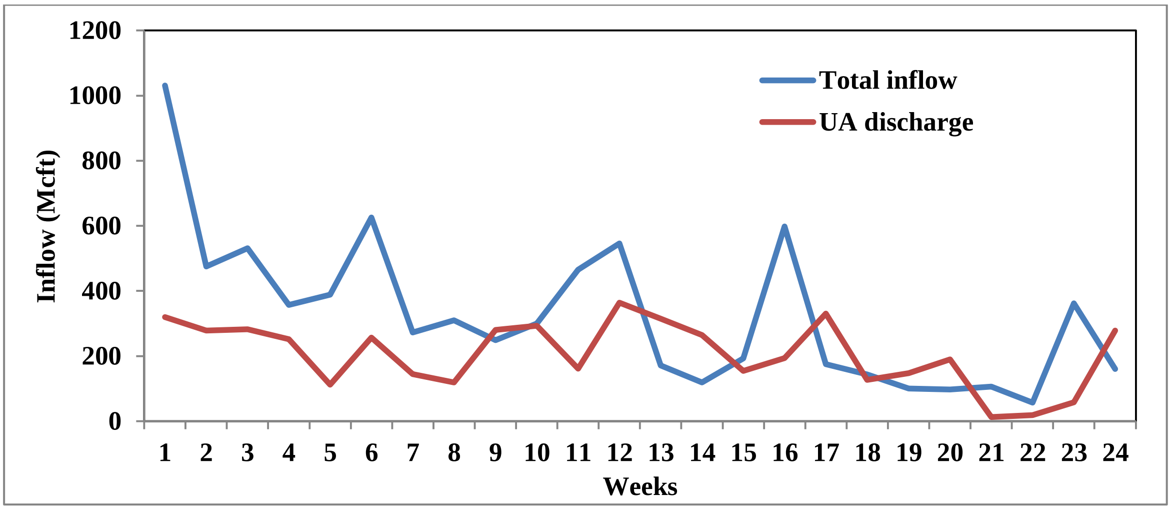


Figure 4.13 Plot for inflow versus outflow (2007)

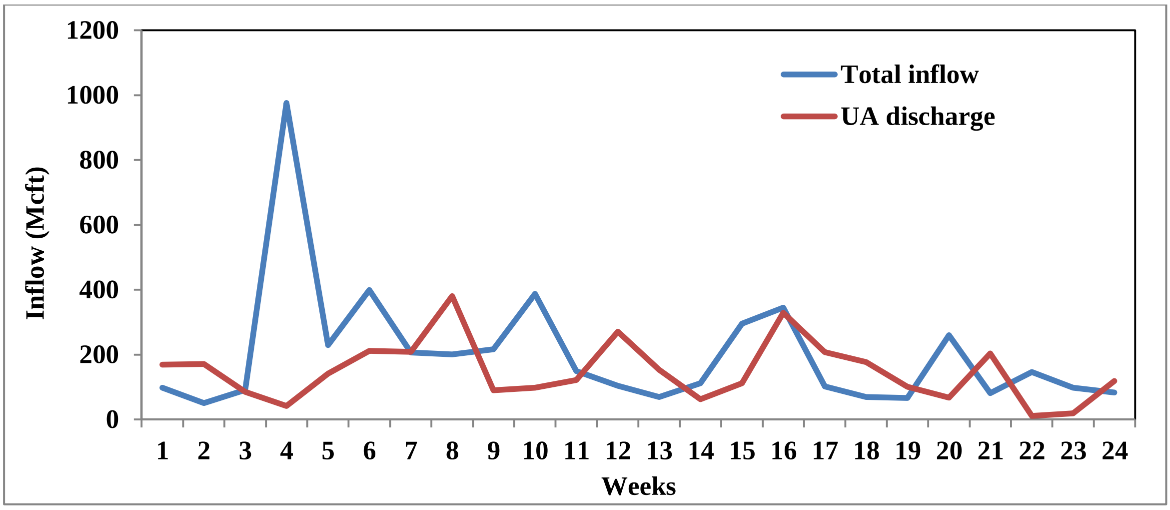


Figure 4.14 Plot for inflow versus outflow (2008)

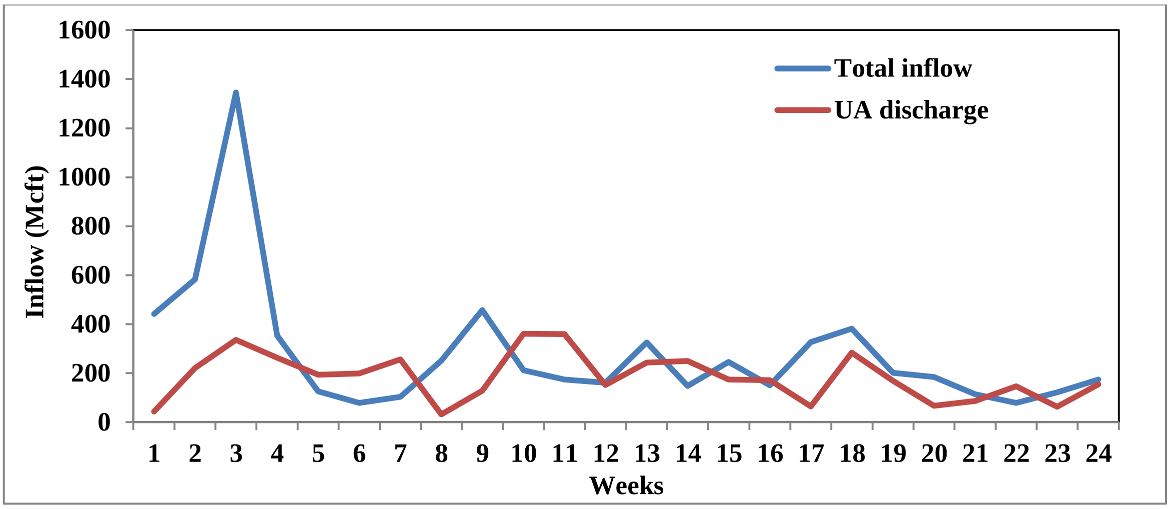


Figure 4.15 Plot for inflow versus outflow (2009)

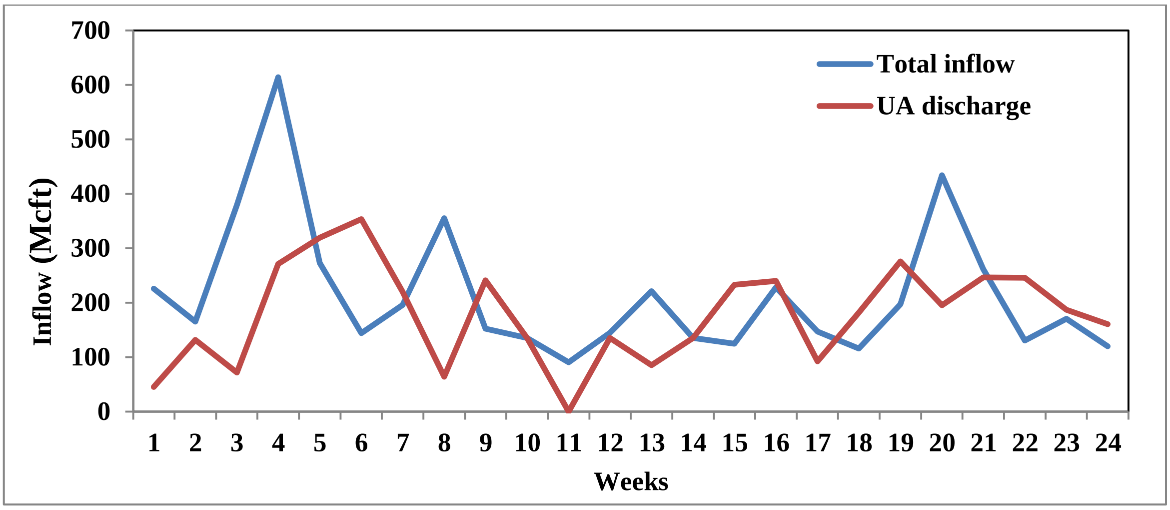


Figure 4.16 Plot for inflow versus outflow (2010)

Table 4.3 Weekly mean and ratio of inflow and outflow

Sl. No.	Year	Mean weekly inflow (Mm^3)	Mean weekly outflow (Mm^3)	Ratio of inflow to outflow	Generation (MU)
1	2006	209.469	210.496	1.004	581.45
2	2007	326.470	206.510	0.632	427.82
3	2008	201.387	147.861	0.734	456.58
4	2009	280.952	184.316	0.656	291.72
5	2010	215.018	177.813	0.827	498.81

Table 4.4 Standard deviation of inflow and outflow

Sl. No.	Year	Standard deviation of weekly inflow (Mm^3)	Standard deviation of weekly outflow (Mm^3)
1	2006	120.503	108.343
2	2007	228.435	100.449
3	2008	195.469	91.857
4	2009	262.535	97.396
5	2010	122.590	90.605

The analysis reveals the following factors.

- By analysing the inflow and outflow from the years 2006 to 2010, the weekly release during the month of July is higher than the weekly inflow of the corresponding months. The release during the other months is higher or lower than the inflow. This clearly indicates that the inflow is not the only deciding factor for the release from the reservoirs.
- The mean weekly release during the year 2006 is almost equal to the mean weekly inflow. The other constraints such as power demand and grid frequency forced to release less water even though the inflow during the years from 2007 to 2010 is high.
- The highest power production is achieved during the year 2006 and it is directly proportional to the ratio of inflow to release of water from the reservoir.
- The fluctuation in the standard deviation of inflow clearly indicates the inflow does not follow a pattern and hence the operation of pumped storage schemes depends on other factors.

These analysis and the above conditions would facilitate for framing the reservoir operating rules.

4.8. SUMMARY OF THE SIMULATION

The quantity of the spill before and after simulation is shown in the following Table 4.5.

Table 4.5 Quantity of the spill before and after simulation

Year	Spill (Mcft)		
	Actual	After simulation	
		Kadamparai dam	Upper Aliyar dam
2006	3	0	0
2007	2639	663.93	72.53
2008	84	0	368.75
2009	1478	505.9	127.76
2010	0	0	116.49
Total	**4204**	**1169.83**	**685.53**
Total spill before simulation			4204.00
Total spill after simulation			1855.36
Total spill reduced			**2348.64**

The different scenarios of combined storage are given in the Figure 4.17. The average combined storage is the average of 10 years combined storage of Kadamparai and UA reservoirs. The simulated combined storage is the average of five years simulated results from 2006. The plot for the year 2007 - 08 reveals the maximum level maintained at the reservoirs during the months of July, August and September.

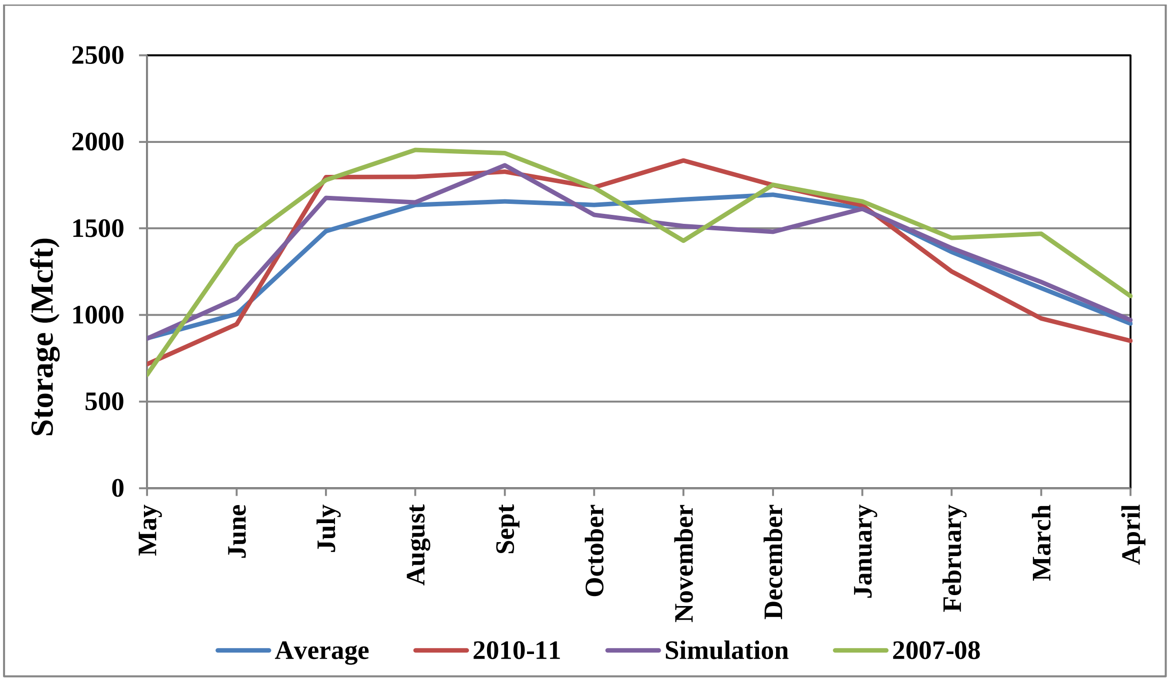


Figure 4.17 Combined storage for 10 years average, simulation, 2010 – 11 and 2007 – 08

From the study of the graphs plotted above, it is understood that the average combined storage curve is better than simulated combined storage curve. But the curve derived from the simulation has minimized or nullified spill. At the same time, a point should be kept in mind that the simulation for the year 2006 would affect the next year operation. Similarly, the simulation of the year 2010 may also affect the next year operation. Since the reservoir utilised maximum possible limits and also it was poor inflow year. As per the storage is concerned, the year 2010-11 can be considered as ideal storage year for running the plant in a most efficient way. The state experienced severe power shortage in this period. So the KPSP utilised to the maximum extent to meet out the critical needs of the grid. Even this year was a poor inflow year but the reservoirs were utilised to the maximum extent for the above reason. So for future operation, following this 2010-11 storage pattern with effective pumping and generation can give better performance of the system. The maximum, minimum and average storage limits from simulation and past 10 years actual operation are listed in the following Tables 4.6, 4.7 and 4.8.

Table 4.6 Combined storage level from simulation

	July	August	September	October	November	December
Average	1676	1650	1865	1578	1514	1480
Max	1855	1918	1966	1916	1948	1949
Min	1471	1322	1550	1336	1356	1155

Table 4.7 Combined storage level from 10 years historical pattern

	July	August	September	October	November	December
Average	1484	1635	1655	1636	1666	1695
Max	1871	1954	1912	1923	1921	1906
Min	424	1284	1292	1025	1381	1284

Table 4.8 Combined storage level from 10 years historical pattern

	January	February	March	April	May	June
Average	1616	1364	1155	950	866	1006
Max	1914	1663	1468	1234	1453	1515
Min	1182	845	821	675	409	556

4.9. CONCLUDING REMARKS

A simulation model to check and reduce spill noticed in Kadamparai pumped storage plant has been developed and implemented in this research work. The results obtained from the application of the model indicate possibility of improvement over the existing operating policies. Operating rules have been framed based on existing operating condition and compared with the simulation results. Model developed has been tested by changing reservoir outflows during monsoon season. Results indicate additional power production, less spill and stressed the need for a lesser storage in the lower reservoir than to maintain it very close to the full reservoir level.

Being of almost equal capacity of upper and lower reservoir, gradual increase of storage in the lower reservoir is causing concern in its optimal operation during monsoon season and also during “must run” conditions. “Must run” condition is to be satisfied while maintaining a lesser storage in the lower reservoir besides power station scheduled operations [Refer Table 4.9].

Table 4.9 Possible hours of generation in critical condition*

Sl. No	KP Dam storage	UA Dam storage	Combined storage	UAPH discharge	Storage / discharge	Hours
1	950	250	1200	Nil	700/16	44
2	850	350	1200	Nil	500/16	31
3	750	450	1200	Nil	300/16	19
4	650	550	1200	Nil	100/16	6

***Assumptions:**

- No inflow on both the reservoirs and Kadamparai power house is operated to its full capacity
- Combined storage kept at 1200 Mcft for example.

Maintaining the combined storage is an important parameter for pumped storage operation. The above simulation results have shown the increased system performance with minimum spill. However maintaining storage for the operation of the individual reservoir is also an important factor in improving the overall performance of the system effectively and with minimum spill, which depends on the storage capacity of the reservoir, inflow pattern and discharge capacity through machines. Since the upper reservoir has got more machine capacity, inflow recorded so far has been found utilized without any spill. Guidelines have been derived from the simulation results, by considering the historical performance of the plant operation during various monsoons and considering the grid requirement. Main recommendation is made for lesser storage in the lower reservoir during monsoon periods to accommodate more water from the upper reservoir.

Based on the historical rainfall data, considering the use of the station as a pumped storage with the present regional grid conditions, plant availability for summer/critical period, for utilizing surplus wind power during monsoon periods and the difficulty in predicting the monsoon inflow condition followed with a reasonable storage is of complex in nature. Hence it is recommended to maintain lesser storage at Upper Aliyar till the end of November so as to obtain improved output with minimum spill during monsoon.

The following guidelines are derived from simulation results and historical performance of the system.

- Maintain UA dam level below 30% of its gross storage up to November 15^{th}.
- From July to November the combined storage should not exceed 1800 Mcft (since maximum one day natural inflow recorded is approximately 200 Mcft during past 5 years).
- The capacity of UA dam should not be increased above 800 Mcft in winter season.
- Operate UAPH to the maximum extent possible during winter period especially if the inflow is continuous, so that storage is limited below 800 Mcft.
- It is recommended if the monsoon is heavy and continuous, keep the lower reservoir storage at an optimum capacity between 700 Mcft to 800 Mcft with a combined storage of 1600 Mcft.

The recent guidelines of CERC insists higher frequency range, which is very near to 50 Hz and imposing more reforms in the grid operation in India, the constraints on power input for motor operation with required frequency for pumping operation would be eliminated for a flexible operation of Kadamparai pumped storage with better output and less spill. This would be possible only when lesser storage is maintained.

Further continuous research is necessary considering the impacts of climate change in future. Maintaining optimal storage level at lower reservoir is recommended for the present condition and it may still be reduced based on future increased operation of the station. It is the only way to reduce spill in an effective manner and to the extent possible based on the storage condition maintained.

Further, the following factors has been observed from this analysis,

The model only concentrates on generation and has not considered the pumping since pumping always depends on the grid frequency. In simulation, few places i.e. 30 August, 13 October 2008, etc spill has occurred. For operational/simulation flexibility, those spills have been pumped up. The above incidents strongly indicated that pumping is essential for achieve higher operational benefits.

However, the limited frequency band availability in the southern grid as well as severe load shedding of TANGEDCO limits the pumping operation as mentioned in

Chapter - 3. Increased pumping operation can surely improve the plant performance considerably. Variable speed drives may be a suitable option in this regard. In the Kadamparai plant power house, space for future implantation (for variable frequency converters) also available.

The following chapter analyzes the feasibility of variable speed drives in Kadamparai pumped storage plant.

Chapter 5
VARIABLE SPEED OPERATION OF REVERSIBLE PUMP-TURBINES AT KADAMPARAI PUMPED STORAGE PLANT

5.1. INTRODUCTION

While carrying out renovation and modernization, introducing new technologies for improving the power station performance is a universal practice. In this context a study has been conducted for Kadamparai pumped storage plant, with the objective of adopting variable speed technology while undertaking renovation & modernization in not-so distant future. Present peak power demand and the expected capacity addition through thermal, nuclear, solar, wind energy power plants to the state grid needs a review on the existing operation of Kadamparai pumped storage plant to meet out the peak and energy shortage of the state. The existing conventional synchronous machines of this plant can be operated as variable speed machines by adopting static frequency converters (SFC) between stator and grid supply or replacement of existing synchronous machines with variable speed induction generators to utilize the grid load variation effectively. Annual operation of Kadamparai pumped storage scheme with variable speed machines has been analyzed in the existing hydraulic conditions. Additional benefits that is likely to accrue as compared to conventional synchronous speed operation has been calculated. Results show that the variable speed technology has considerably increased the plant performance.

Variable speed operation is the latest technology in pumped storage operation and many PSS, which have recently been commissioned, are operating with this technology worldwide [33], [38], [63]. Most of the experiences of variable speed pumped storage operation are traced to Japan, where there has been a need for developing such schemes to improve stability and frequency control of the power system. Yagisawa power station in Japan is the first converter-fed adjustable speed pumped storage plant of the world, which was commissioned in the year 1990 [33]. In Europe, the variable speed pumped storage was under research for many years and the Goldisthal pumped storage plant of Germany with two 300 MW variable speed units have been put into operation in 2004 [96].

Even though the pumped storage schemes are being used since many decades by the power systems, variable speed pump-turbines are found very less in their ratio as compared to the fixed speed installations as this technology is only slightly more than two decades old. However, almost all the recent pumped storage plants are adopting variable speed technology due to their inherent advantage of higher efficiency. The following Table 5.1 shows some of the major variable speed pumped storage plants of the world and their specific characteristics. The Table 5.2 shows the installed and planned pumped storage developments in Europe and United States.

Table 5.1 Major variable speed pumped storage plants around the world

Plant name	Country	Capacity (MW)	Remarks
Yagisawa (1990)	Japan	1 x 85	First converter-fed plant of the world [33].
Goldisthal (2004)	Germany	2 x 300	Largest cyclo-converter of the world [96].
Ohkawachi (1993)	Japan	2 x 400	Largest variable speed unit of the world [63].
Tehri (Under construction)	India	4 x 250	Large head variation site in the world [19].

Table 5.2 Installed and planned pumped storage developments in Europe and U.S. [80]

2000 - 2010	**Total (MW)**	**Conventional PS (MW)**	**Ternary (MW)**	**Variable speed (MW)**
Europe	2,443	836	547	1,060
North America	0	0	0	0
2011 - 2020	**Total (MW)**	**Conventional PS (MW)**	**Ternary (MW)**	**Variable speed (MW)**
Europe	11,562	6,849	303	4,410
North America	40	40	0	0

Conversion of existing fixed speed pumped storage by variable speed machine during renovation and modernization is a new area of study. This aspect has been studied for the Kadamparai pumped storage scheme since the plant is under operation for more than 26 years. Further, the expected capacity addition through thermal (Mettur, North Chennai, etc.), nuclear (Kudankulam) and the existing wind energy (approximately 7000 MW) and proposed solar of 3000 MW of Tamil Nadu State grid needs a review of the existing operation of Kadamparai pumped storage with the aim to improve its performance.

This chapter analyzes the technical benefits achieved by using the variable speed technology for the existing Kadamparai pumped storage plant. An analysis has been carried out by using five year (2006 – 2010) plant operational data. The benefits of variable speed operation over conventional synchronous speed operation have been determined.

Since peak shortage always exist in India and also in Tamil Nadu state grid, this study would be helpful in availing additional benefits through variable speed operation.

5.2. VARIABLE SPEED HYDRO/PUMPED STORAGE OPERATION

Hydro power plants are designed to operate at the maximum efficiency corresponding to rated synchronous speed. The hydro turbines are designed to run at rated speed under design head and wicket gate opening to attain maximum efficiency [55].

The performance of hydro turbine depends on the rotational speed and is designed to operate at its best achievable efficiency for a particular speed i.e. synchronous speed. As this rotational speed is a function of head, the performance of the turbine is affected by the head variation as it cannot rotate at synchronous speed over the entire range of head variation. Hence it is necessary to adjust the rotational speed of the turbine to its maximum possible efficiency for a particular head. On the contrary, if the turbine is allowed to run at a speed corresponding to the head available, it shall run at an efficiency, which shall be higher than best attainable efficiency corresponding to the synchronous speed. However in that event, the generator shall be operating with variable frequency, which needs to be modulated to the system frequency for enabling parallel operation [35], [78].

Initially variable speed technology was used for wind generators to maximize its operating efficiency to the stochastic nature of wind energy. The ratings of these machines are limited to kilo-watt (kw) range [15], [64], [71]. The development of modern power electronic devices has enhanced the operational range to megawatt range, which makes these systems suitable for the hydro power applications including pumped storage schemes [41], [76], [95].

The variable speed operation in a hydro power plant can be achieved by any one of the following two systems [48].

- **For synchronous machines –** introducing a static frequency converter (SFC) between stator and grid interconnection.
- **For doubly fed wound rotor asynchronous machines (DFAM) –** introducing either a cyclo-converter or a Gate Turn-off Thyrister (GTO) converter in between grid supply and rotor.

The first system has not been found to be eminently suitable for synchronous units above 250 MVA. Above 250 MVA, static frequency converters are generally not being recommended because the rating of the power electronic devices used must be equal to the unit rating, since the machines are powered by SFC which is directly connected to the stator [48]. The second system of doubly fed wound rotor asynchronous machine is the latest technology in this field and the variable speed can be achieved for the range up to 500 MVA with DFAM [48]. In this technology, only slip power is fed to the rotor through power electronic converters; thus the required rating of converters is considerably less i.e. about 20% to 30% of unit rating [49]. The latter solution have been found to be more economical offering better dynamic response over a wide speed range [48]. The schematic diagram of the above two systems are shown in the Figures 5.1, 5.2 and 5.3 [95].

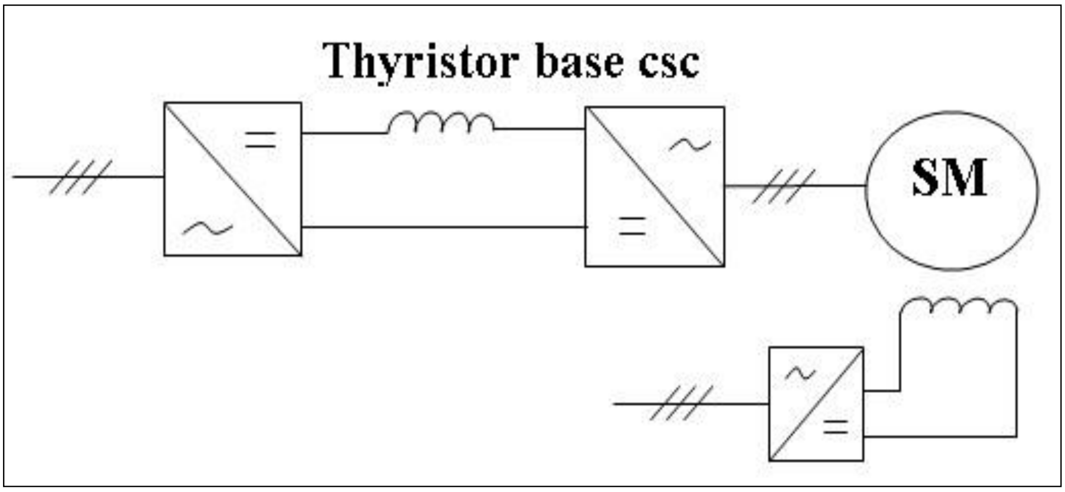


Figure 5.1 Synchronous machine with current source converter

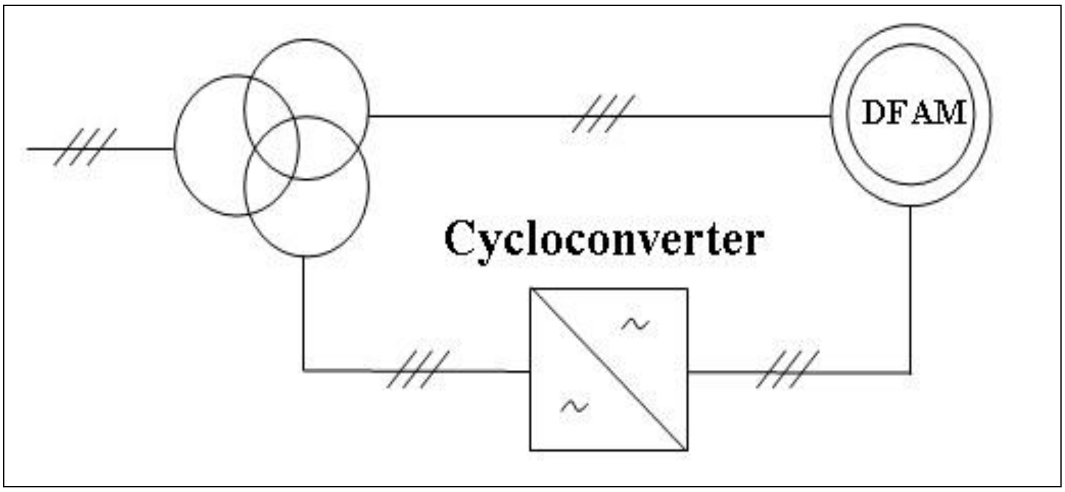


Figure 5.2 Doubly fed asynchronous machine fed with cyclo-converter

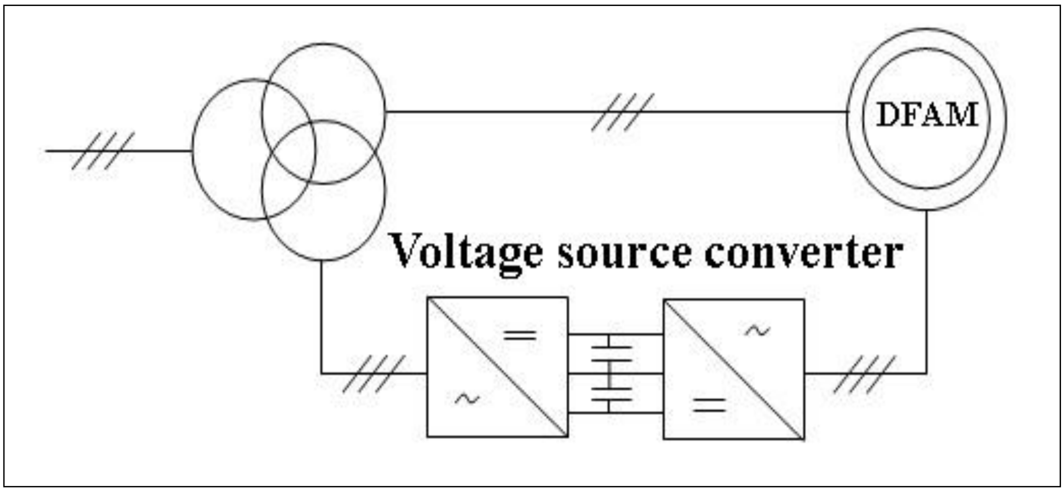


Figure 5.3 Doubly fed asynchronous machine fed with voltage source inverter

The major advantages of the variable speed technology over conventional synchronous speed machines are summarized [74], [85].

- Increase in efficiency and wide operations in generation and pumping mode even under part load.
- Possibility of active power control in pumping mode.
- Network stability improvement by reactive power control.
- Network stability improvement by instantaneous active power injection in the grid (flywheel effect).
- Adaptable to a wide head variation.

In this context, replacing conventional pump-turbines with variable speed pump-turbines could increase the plant efficiency as well as the system efficiency, besides availing other technical benefits such as balancing the grid due to inclusion of more renewable energy sources, frequency regulation during surplus periods, VAR regulations, etc.

5.3. PERFORMANCE UPGRADATION BY USE OF VARIABLE SPEED TECHNOLOGY

In this section, the benefits of variable speed units over conventional speed units of Kadamparai pumped storage plant are presented.

Power input to machine and peripheral velocity factor are functions of head. As the head varies, both power input and peripheral velocity vary consequently. The efficiency of the turbine is also affected (solid lines of the demonstrated hill curves in Figure 5.4). If speed can be adjusted, the operating point can be brought nearer to the maximum possible efficiency for any available head. Hill curves have been used in this study used to extract the efficiencies of the turbines for various head, discharge, and input power level variations. A typical Francis turbine hill curve has been regenerated for this study [55] and is shown in the Figure 5.4.

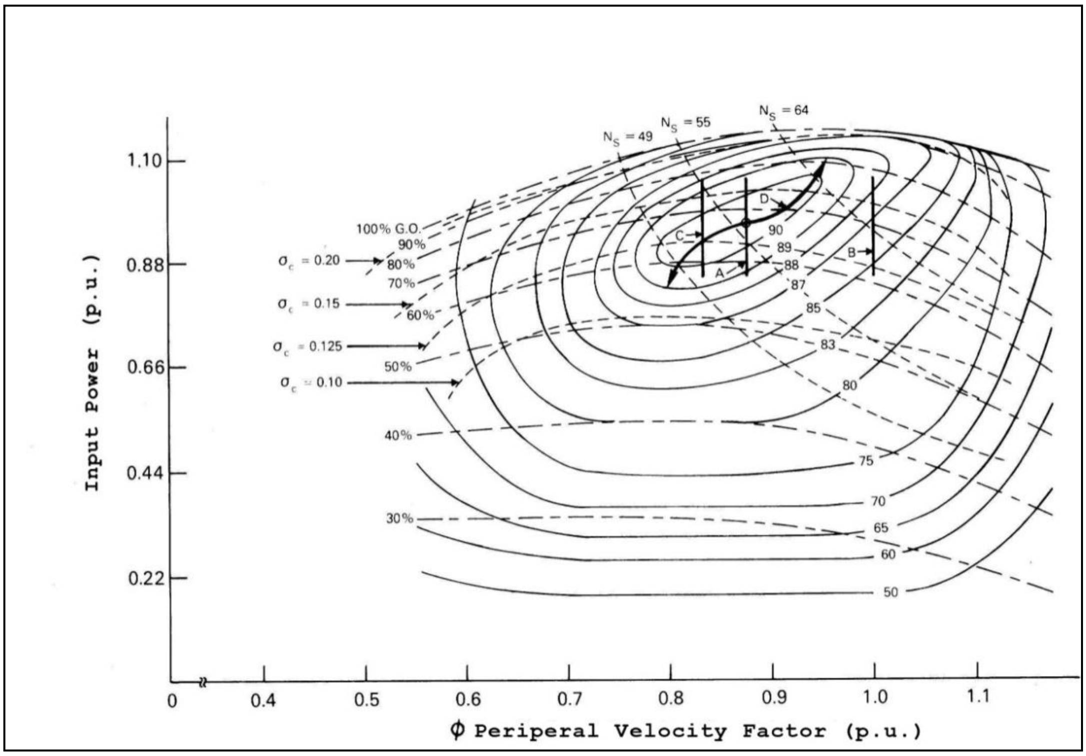


Figure 5.4 Hill curve for a model Francis turbine

The solid lines of the hill curve represent various efficiencies. The dotted lines demonstrate locus of fixed gate openings. 'σ_c' is cavitation susceptibility and Ns is the specific speed of the model turbine. The vertical axis of the hill curve implies various input power levels and the horizontal axis shows peripheral velocity factor of the unit dimension model turbine and are generally defined as mentioned in the following equations (1) & (2).

5.4. PROBLEM FORMULATION

5.4.1. For generation

$$P_{in} = \rho.g.Q_{Design}.H \quad (1)$$

$$\Phi_n = n.D / H^{1/2} \quad (2)$$

Where,

P_{in} → Power input to the turbine in kw

ρ → Density of water

g → Acceleration due to gravity

Q → Discharge in m^3/sec.

Φ_n → Peripheral velocity factor

n → Rotational speed in rpm

D → Diameter of the turbine runner in meter

H → Net head in meter

5.4.1.1. Known parameters

Net head	=	341m
Rated Output Power	=	100 MW
Rated discharge, Q	=	34 m^3/sec.

5.4.1.2. Calculation of base units

No of poles	=	12
Rated speed, N	=	120f / P
	=	500 rpm

Where,

f → Rated frequency in Hz

P → Number of machine poles

5.4.1.3. Calculation of peripheral velocity factor

Peripheral velocity factor is depends on the three parameters speed, diameter of turbine vanes and head. Hence if speed is keeping constant then peripheral velocity factor varies as head varies.

Peripheral Velocity Factor, Φ_n = $n.D / H^{1/2}$

5.4.1.4. Calculation of base peripheral velocity factor

Base Peripheral Velocity Factor, $\Phi_{n\ Base}$ = $N \times 3.5 \times H_{Net}$

= $500 \times 3.5 / (341)^{½}$

= 94.768

5.4.1.5. Calculation of peripheral velocity factor p.u.

Peripheral Velocity factor (p.u.) = Φ_n / Φ_{Base}

5.4.1.6. Calculation of power input

Power Input = g x Q_{Design} x H kW

Rated Power Input = 100 MW / (0.98 x 0.92)

= 110.91 MW

5.4.1.7. Calculation of power input p.u.

Power Input (p.u.) = Power Input / Rated Power Input

= Power Input / 110.91

5.4.1.8. Calculation of efficiency

- Power input (p.u.) and peripheral velocity factor (p.u.) corresponding to various head variations have been computed from equations (1) & (2).
- Corresponding to per unit (p.u.) input power and per unit (p.u.) peripheral velocity factor for various heads, efficiencies have been derived from the hill curve for fixed speed.
- By adjusting the speed (±10% of synchronous speed [48], [55]) corresponding to maximum efficiency point of the turbine corresponding to the same power (power for which fixed speed efficiencies derived), various efficiencies have been calculated for variable speed operation.
- Efficiencies of variable speed and fixed speed operation have been compared.

5.4.2. Pumping

Base input power = 110 MW

Power input Electrical, P_{in} = g x Q x H / η

So,

Discharge, Q = P_{in} x η_P x η_M / (g x H)

Where,

P_{in} = Electrical power input for pumping, in MW

η_M = Motor efficiency

η_P = Efficiency as pump (assumed as same as turbine for reasons stated in para 5.4.2.2) g = Acceleration due to gravity

H = Pumping head, in meters (including static and dynamic heads)

Additional discharge pumped ($Q_{Additional}$) = Discharge pumped with variable speed – Discharge pumped with constant speed

5.4.2.1. Suggested speed corresponding to maximum efficiency point for particular head

Peripheral velocity factor, $\Phi = \Phi_{p.u.} \times \Phi_{Base}$

$$\Phi = n.\,D / H^{1/2}$$

$$n = (\Phi \times H^{1/2}) / D$$

New velocity factor p.u. has been obtained corresponding to new efficiency points from the hill curve. Using above equations new speed of rotation has been calculated and these new speeds will be the speed corresponding to the maximum efficiency points.

5.4.2.2. Calculation of pump efficiency

- Peripheral velocity factors corresponding to various head variations have been calculated.
- Corresponding to various peripheral velocity factor and assumed power input, various efficiencies have been calculated for fixed speed operation.
- By adjusting the speed corresponding to maximum efficiency point of the pump mode for same electrical power input (power for which fixed speed efficiencies derived) various efficiencies have been calculated for variable speed operation.
- Discharge (Q) has been calculated for both the operations i.e. Fixed/Variable, corresponding to their efficiencies.
- Additional discharge that can be pumped with variable speed of operation has been calculated.

The efficiencies for both pumping cycle and generation cycle have been extracted from the same hill curve. As per BUTU method, BUTU in Spanish means Pump As Turbine (PAT), the relationship between turbine and pump efficiency is $\eta_T = \eta_P + 0.03$ [69] and Kittredge [56]. It assumes that all pumps with the same specific speed would produce similar head-flow characteristics in the turbine mode. Since the BUTU method has a negligible efficiency step-up by 0.03, Kittredge has assumed that efficiency while operating as a pump may be taken as equal to that while operating as a turbine. Therefore in this analysis pumping efficiency has been considered as equal to the efficiency of generation cycle.

Hill curve methodology as followed by Ciocan et al. [34] to compare the efficiencies of fixed and variable speed operation has been followed in this analysis.

5.5. RESULTS AND DISCUSSION

5.5.1. For generation

The minimum, rated and maximum head for Kadamparai plant are 323 m, 341 m and 395 m respectively in generation mode. The rated discharge for the machine in generation mode is 34 m^3/sec. For these design data, the efficiencies have been derived at every 10 m intervals i.e. from 323 to 395 m from the hill curve (Annexure - 10) as mentioned in the methodology for variable and fixed speed operation. The comparison between these efficiencies is shown in the Figure 5.5. The efficiency and discharge calculation shown in Annexure - 6. From the graph it can be inferred that the efficiency with variable speed operation is higher than the fixed speed operation at lower heads. It is also found that very small increase in efficiency is evidenced at higher heads.

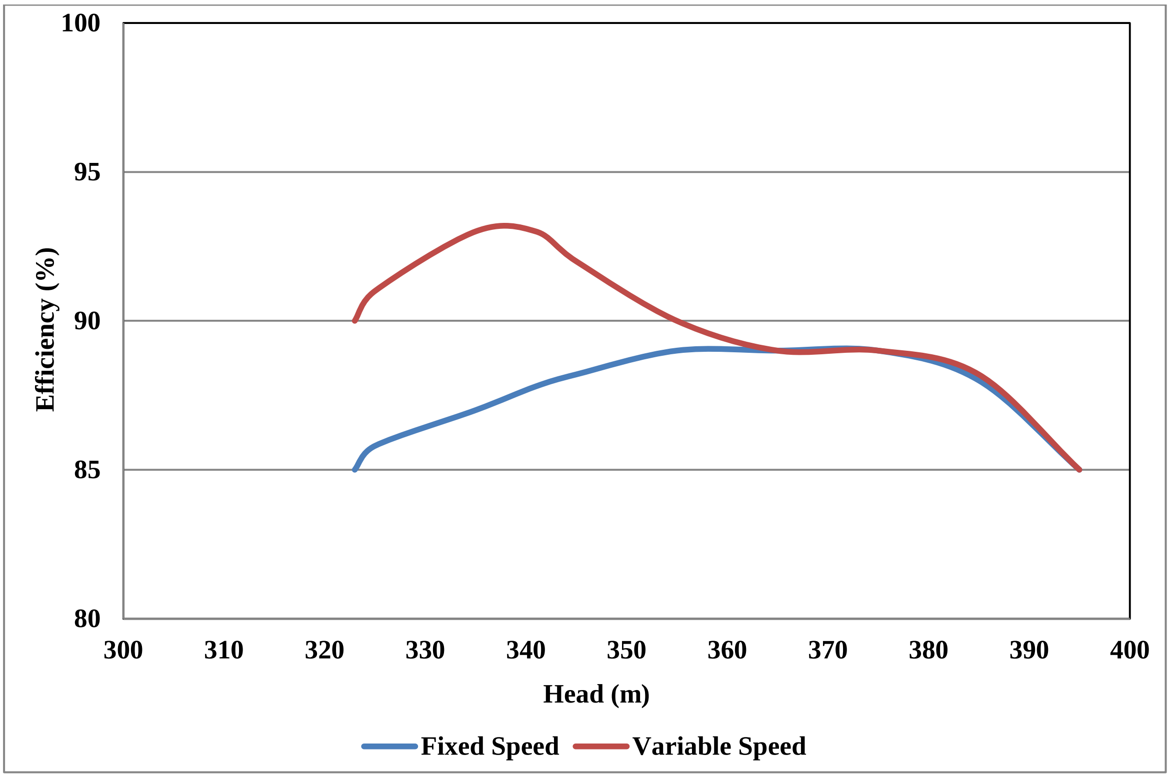


Figure 5.5 Head versus efficiency

5.5.2. For pumping

5.5.2.1. Study of part load behavior

The minimum, rated and maximum head for Kadamparai plant are 341 *m*, 381 *m* and 413 *m* respectively in pumping mode. For these design data, the efficiencies have been derived at every 10 *m* intervals i.e. from 341 to 413 *m* from the hill curve as mentioned in the methodology for variable and fixed speed operation (Efficiency and discharge calculation shown in Annexure - 7).

The pumping operation of pumped storage plant always depends on the grid surplus. In the southern regional grid to which KPSP is connected has shortage of surplus power even during off-peak periods. The available little surplus power could be used effectively by adopting variable speed machines.

Various studies [34], [84] reveal that up to 70% of rated power, pumping can be done efficiently by variable speed machines. The part load characteristics of the Kadamparai pumped storage scheme have been analyzed in this study. The rated pump input of the Kadamparai pumped storage scheme is 110 MW per unit. For analyzing the part load benefits in pumping mode, various power levels i.e. 80 MW, 90 MW, 100 MW and 110 MW have been assumed. The Figures 5.6 - 5.13 shows the efficiencies and discharges for various head for assumed power levels for the sample year 2006 (head variation 365 *m* to 401 *m*). The calculation shown in Annexure - 8 and the hill curves used for this analysis are shown in Annexure - 11.

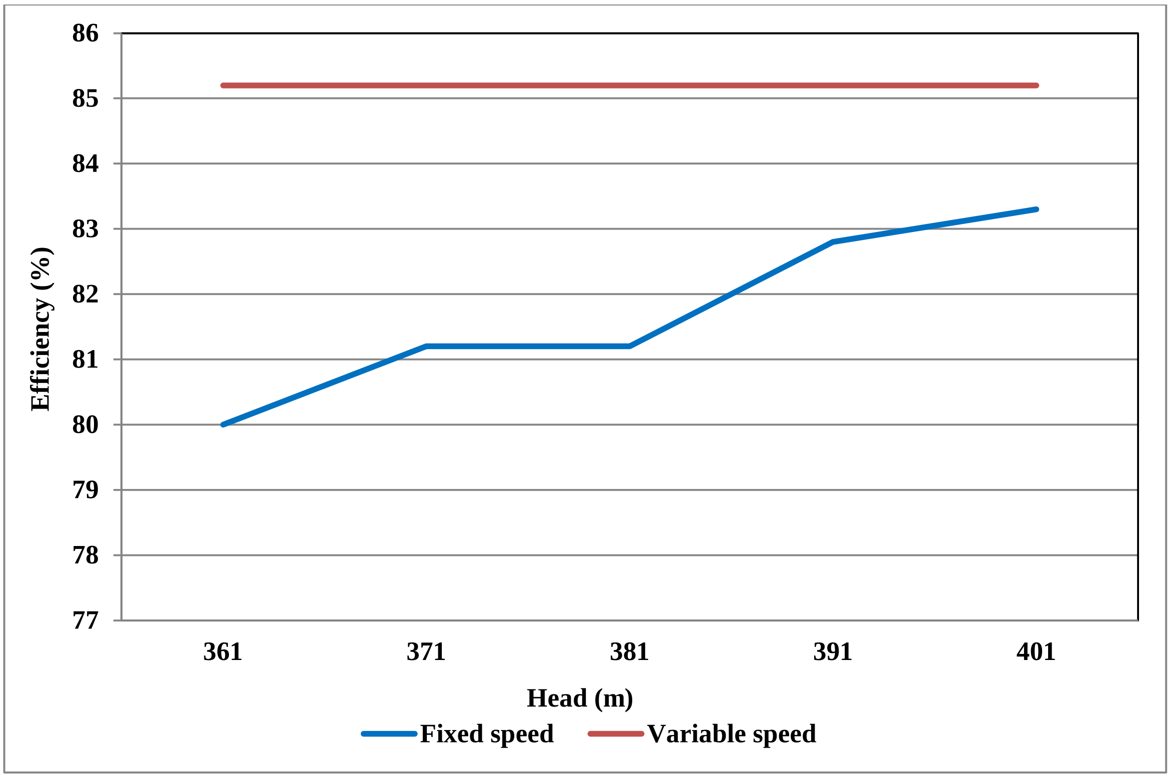


Figure 5.6 Head versus efficiency for 80 MW

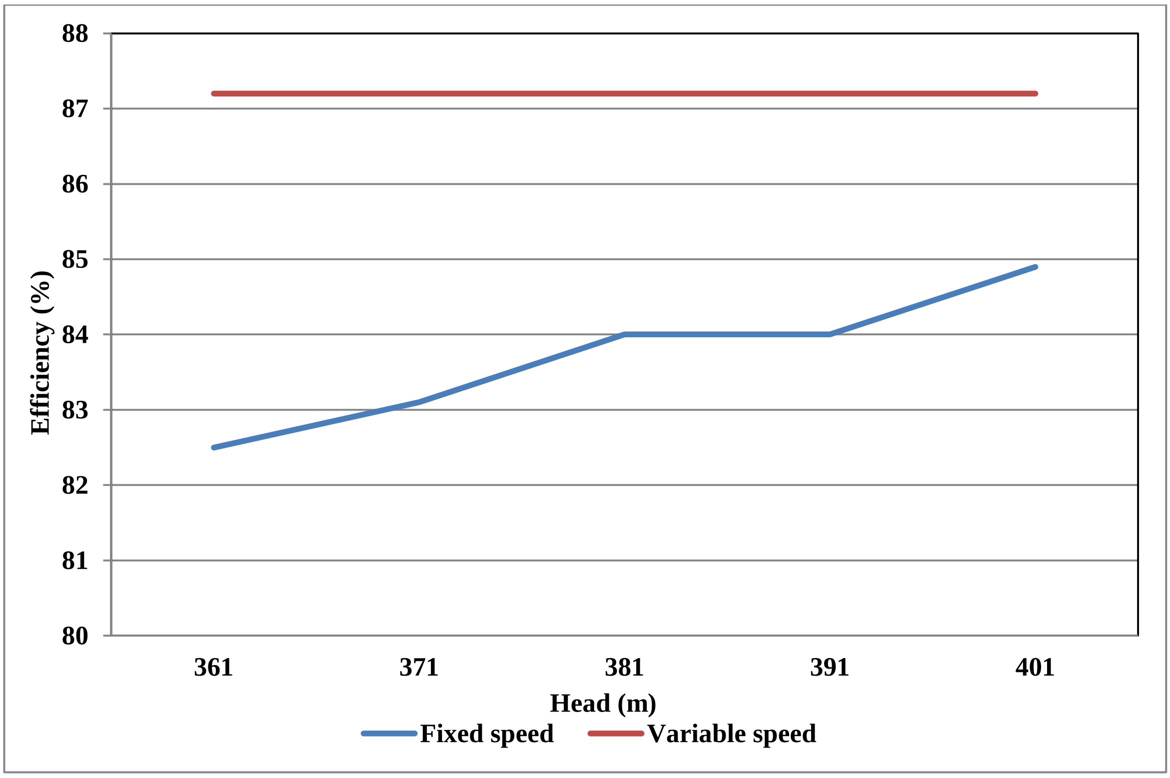


Figure 5.7 Head versus efficiency for 90 MW

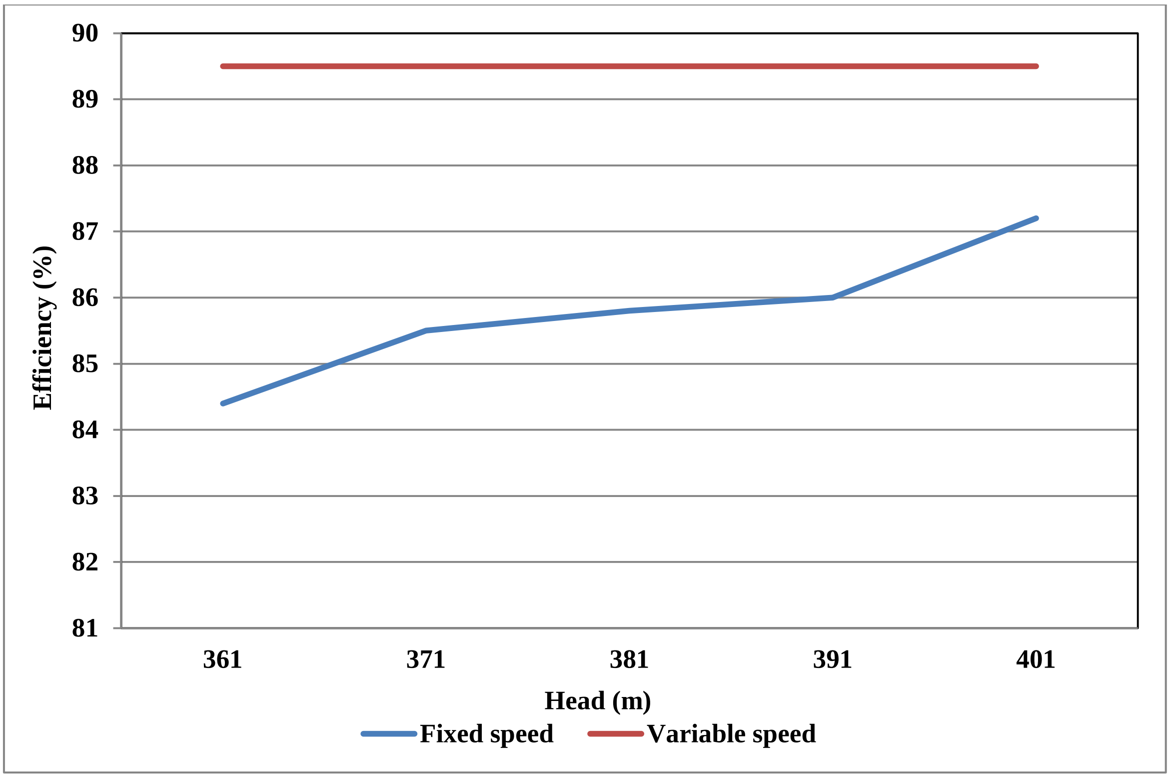


Figure 5.8 Head versus efficiency for 100 MW

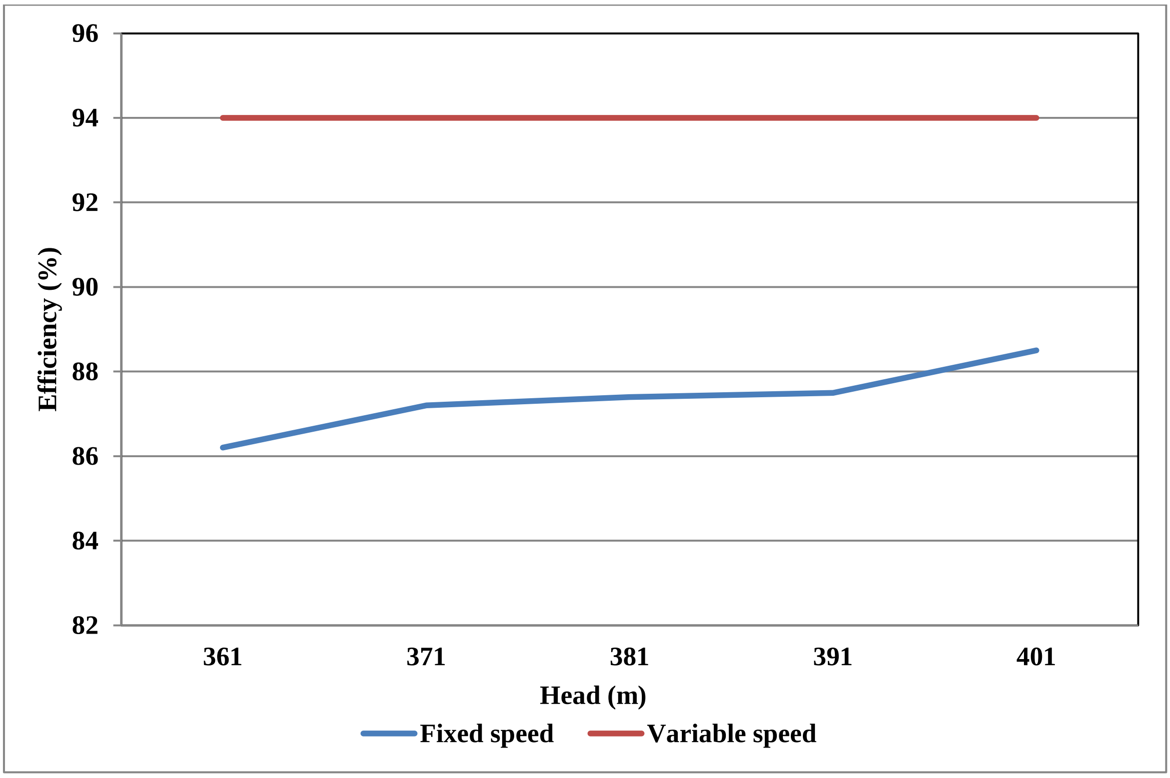


Figure 5.9 Head versus efficiency for 110 MW

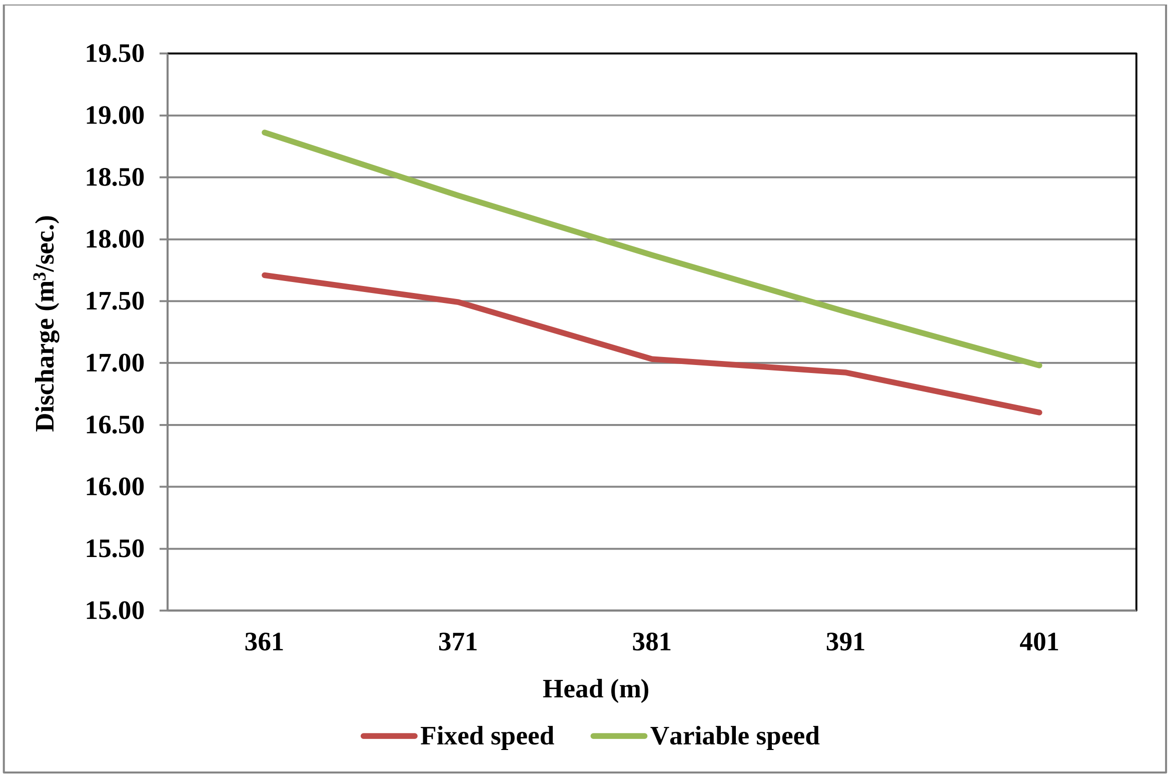


Figure 5.10 Head versus discharge for 80 MW

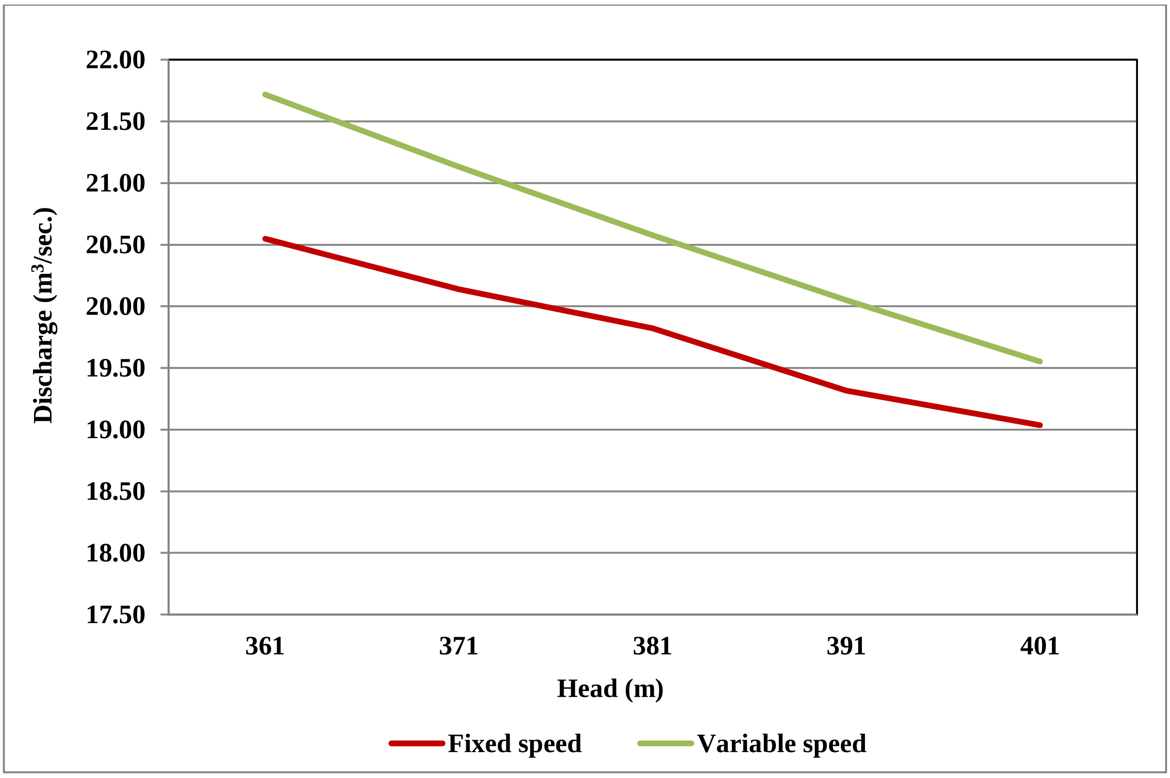


Figure 5.11 Head versus discharge for 90 MW

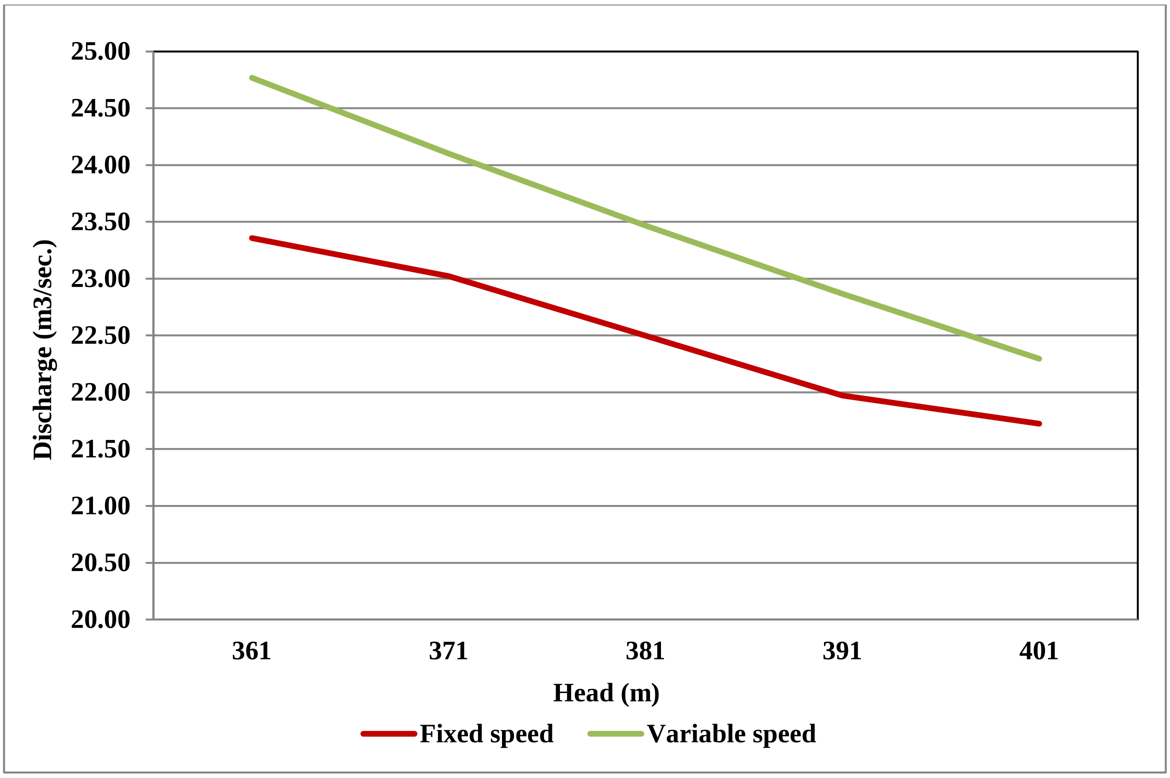


Figure 5.12 Head versus discharge for 100 MW

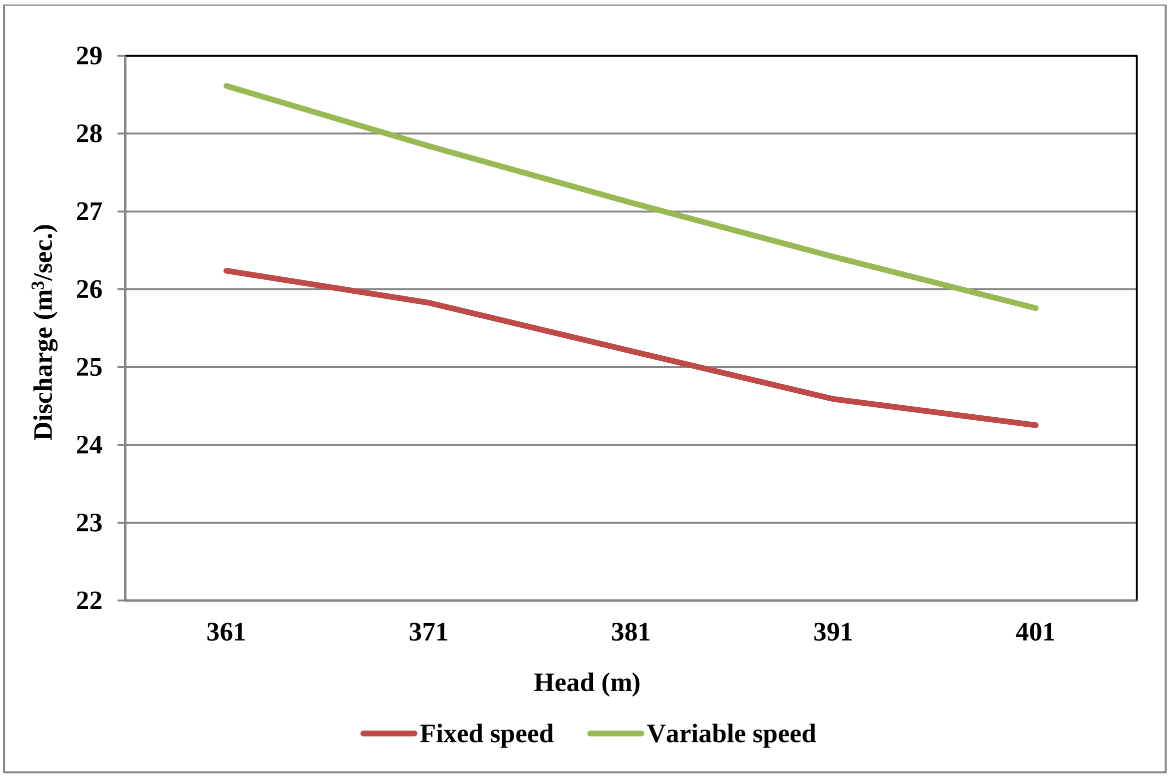


Figure 5.13 Head versus discharge for 110 MW

5.5.2.2. The efficiency-head and the speed

The relationship between the efficiency-head and the optimized speed is the major parameter especially for the renovation. The dependence of the efficiency on the pump speed for various input power level is shown in the following Figures 5.14 – 5.17.

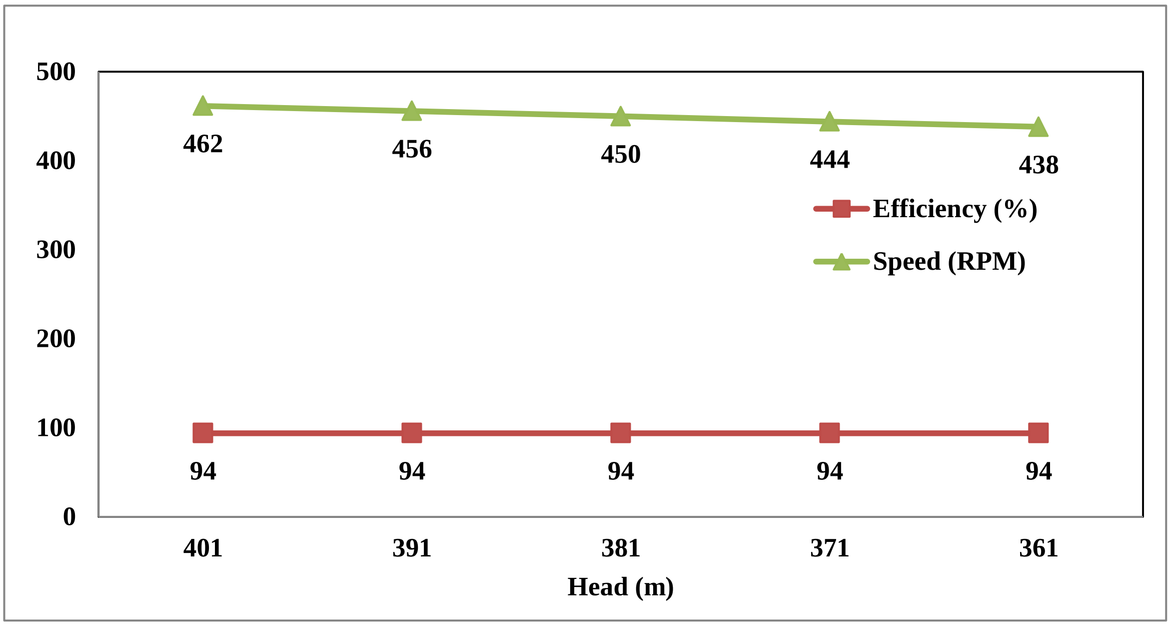


Figure 5.14 Plot for efficiency-head and the optimized speed for 110 MW

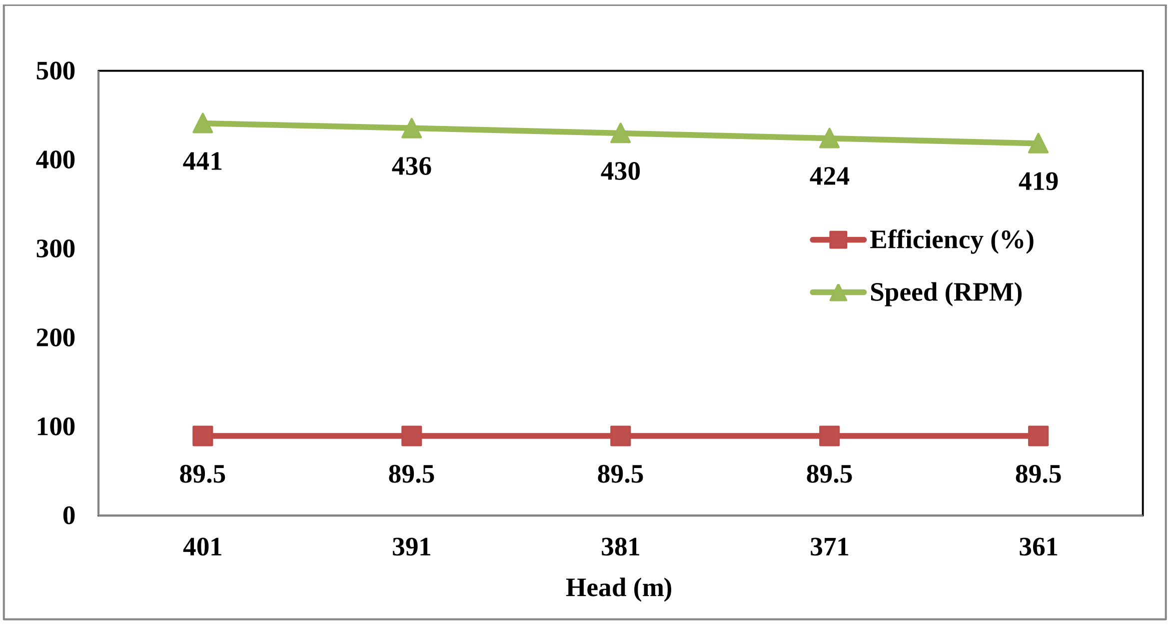


Figure 5.15 Plot for efficiency-head and the optimized speed for 100 MW

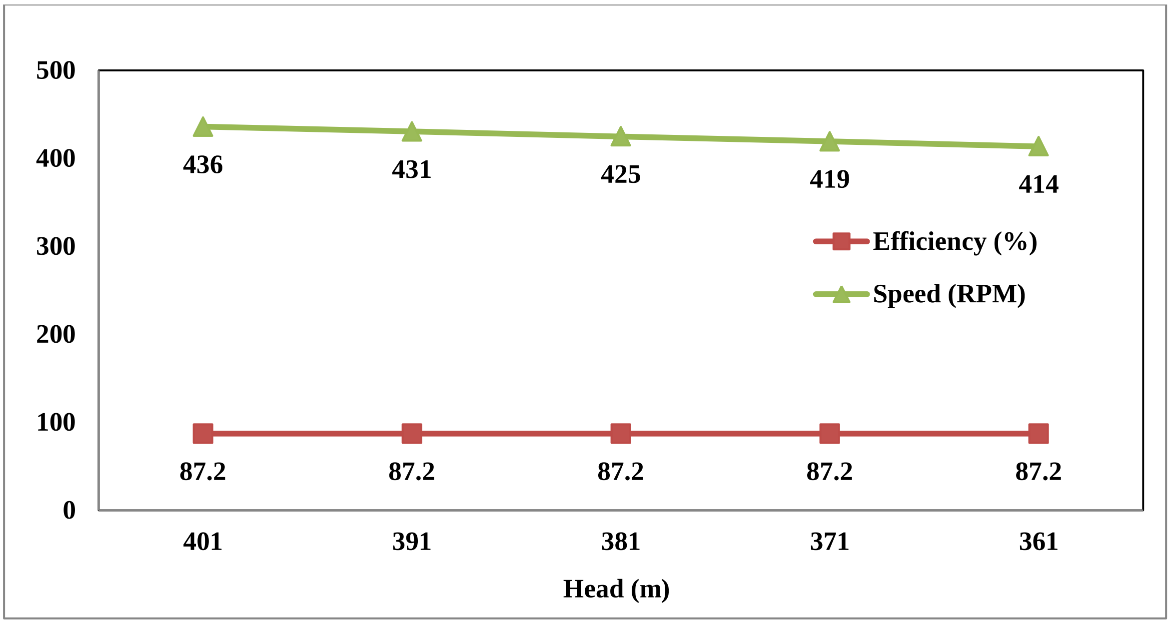


Figure 5.16 Plot for efficiency-head and the optimized speed for 90 MW

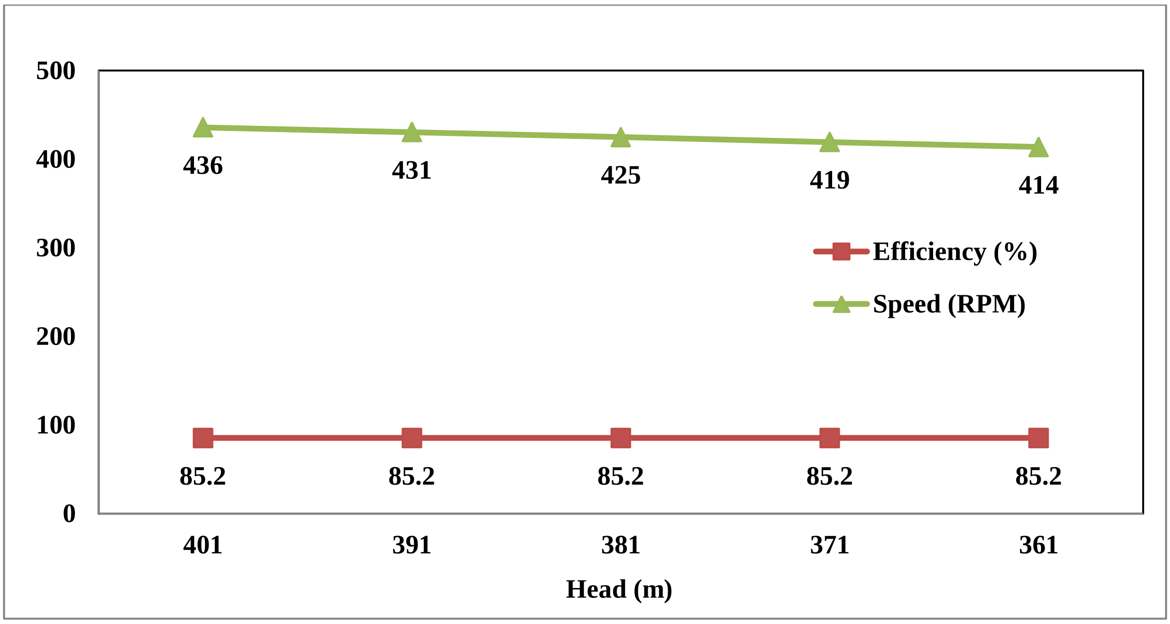


Figure 5.17 Plot for efficiency-head and the optimized speed for 80 MW

5.5.3. Benefits of variable speed pumping in KPSP

For quantifying the benefit of variable speed pumping operation of Kadamparai, five years i.e. 2006, 2007, 2008, 2009 and 2010 real time operational data has been considered for this analysis. A spread sheet model has been developed for this analysis (Annexure - 9). The following parameters have been modeled.

- Daily operating head i.e. static head (The practice is to note down the head level every day morning at 8 A.M. The same data has been used for this analysis and assumed remain constant for whole day pumping operation).
- Daily operating hours of the pump.
- The head loss includes frictional loss, local head loss due to expansion or contraction of the conduits (Estimated by the Darcy-Weisbach formula as mentioned in (Indian Standards) IS 11625 – 1986 & IS: 2951 (Part 2) – 1965).
- Dynamic head derived from static head i.e. static head – head loss.
- The pump discharges for various heads for both fixed and variable speed operation.

For this analysis, the discharge for the rated pump input i.e. 110 MW with variable and fixed speed efficiencies have been calculated by using the following relationship at each 10 m interval of head variation.

$$\text{Discharge, } Q = P_{in} \times \eta_M \times \eta_P / (g \times H)$$

Where,

P_{in} = Electrical power input for pumping, in MW

η_M = Motor efficiency

η_P = Efficiency as pump (assumed as same as turbine for reasons stated in para 5.4.2.2 previously)

g = Acceleration due to gravity

H = Pumping head, in meters (including static and dynamic heads)

The discharges calculated from the above formula have been interpolated for all other heads. The daily pumping volume for variable speed and fixed speed operation have been computed by multiplying the pumped discharge with the number of pumping hours. The following Figures 5.18 – 5.22 show the difference in pumped volume of water between fixed and variable speed pump operation for the years i.e., 2006 – 2010.

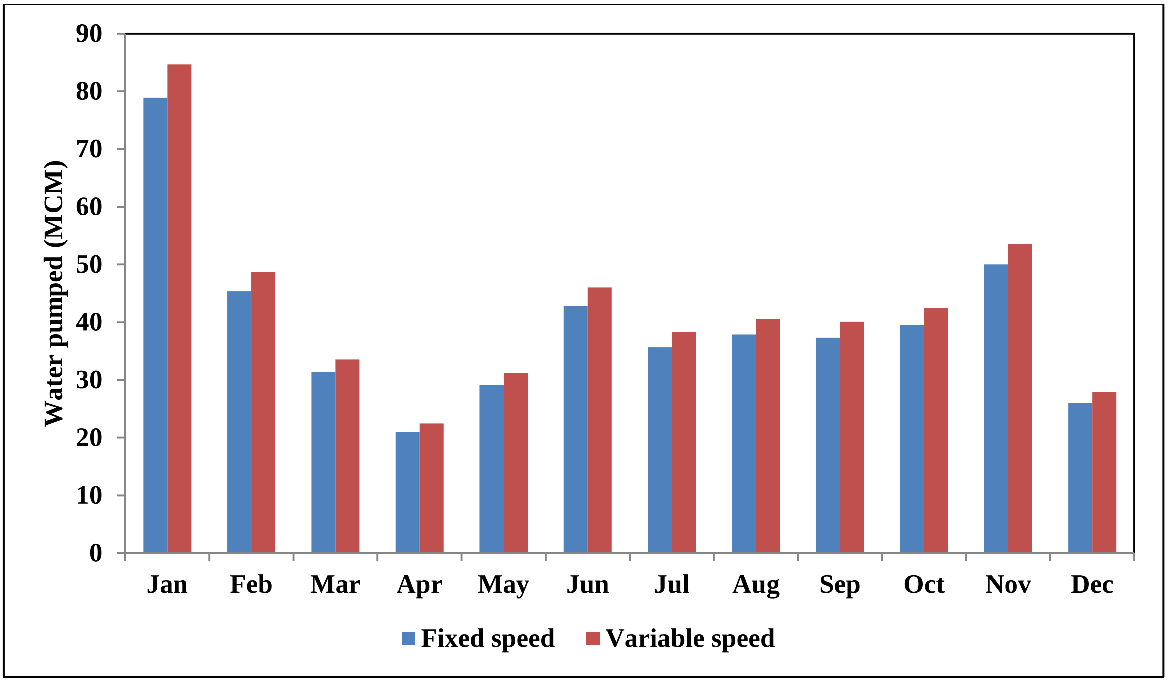


Figure 5.18 Water pumped – Fixed speed versus variable speed operation (2006)

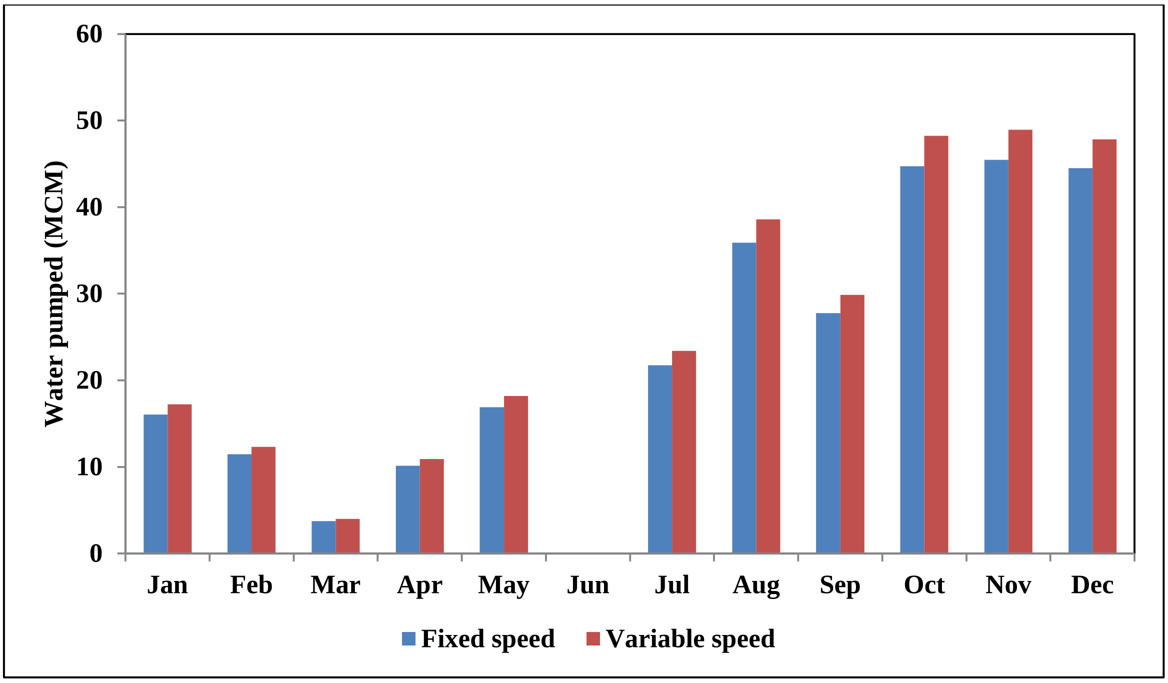


Figure 5.19 Water pumped – Fixed speed versus variable speed operation (2007)

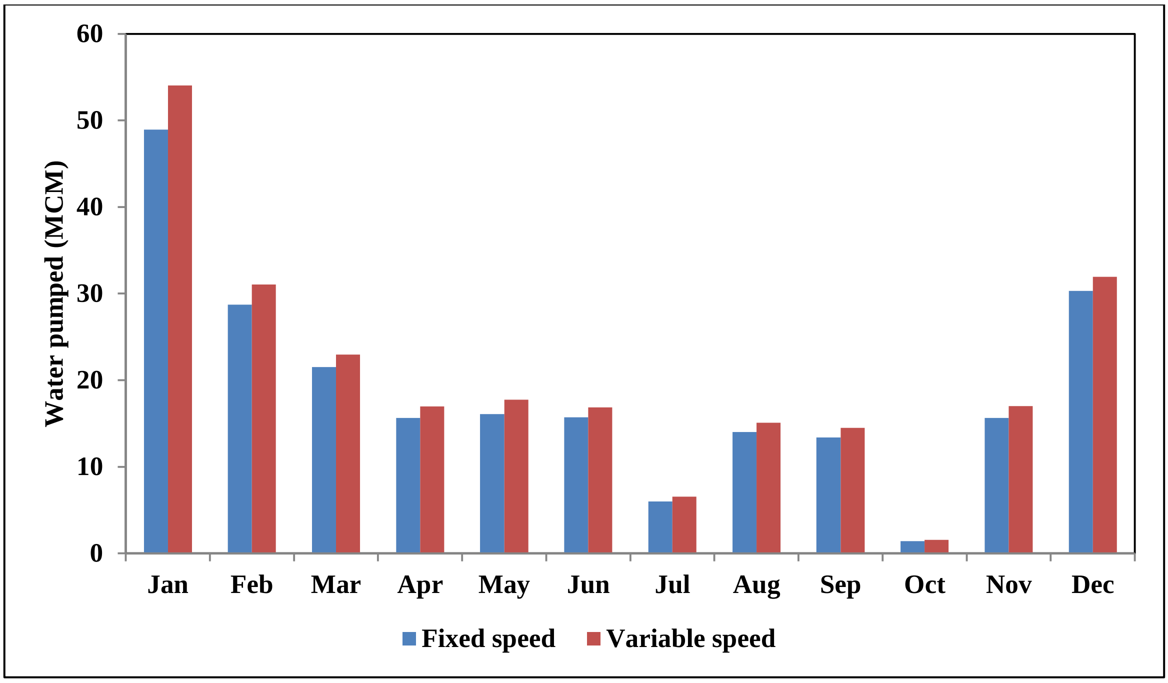


Figure 5.20 Water pumped – Fixed speed versus variable speed operation (2008)

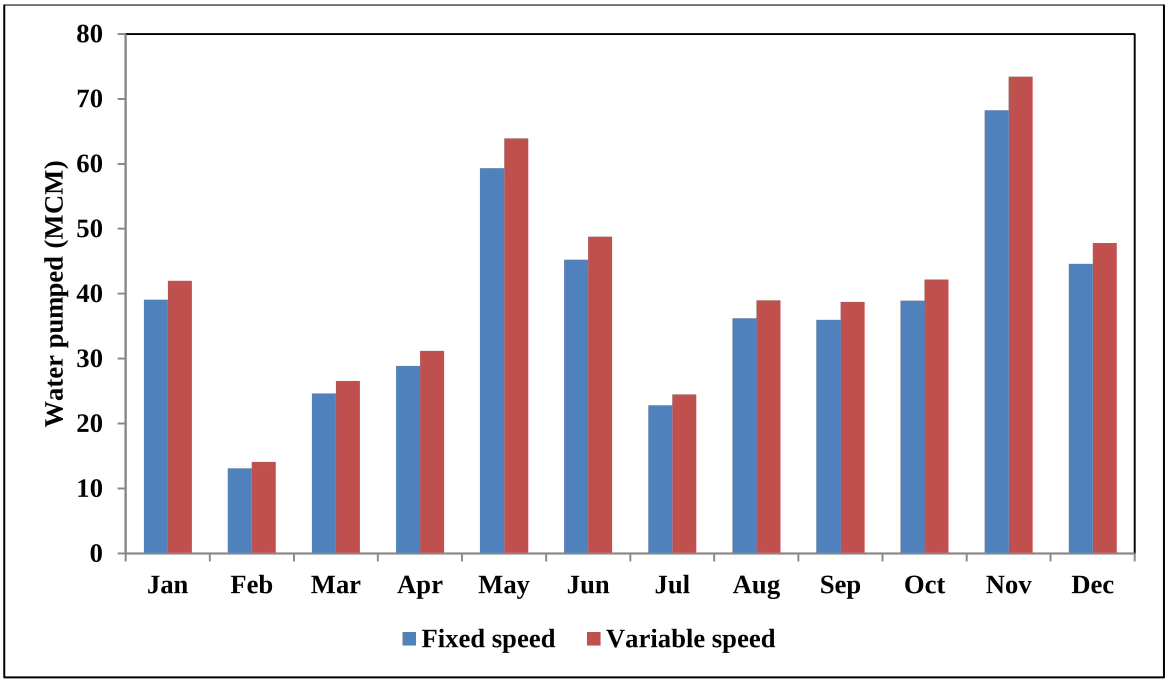


Figure 5.21 Water pumped – fixed speed versus variable speed operation (2009)

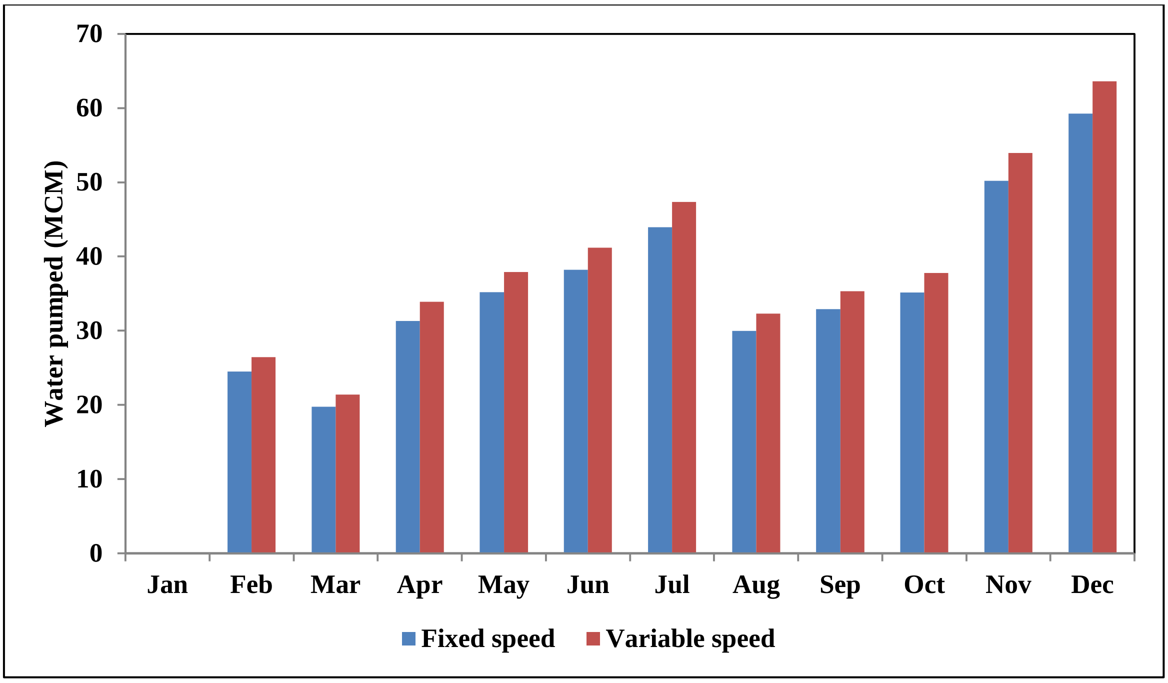


Figure 5.22 Water pumped – fixed speed versus variable speed operation (2010)

For the whole of five years under investigation, the analysis reveals the following results which are shown in the following Table 5.3. Additional water has been pumped from the lower reservoir by adopting variable speed operation, possible additional energy generation from the amount of additional water and percentage of additional energy are presented.

Table 5.3 Results of variable speed pumping analysis for the years 2006 - 2010

Year	2006	2007	2008	2009	2010
Additional water pumped (MCM)	34.39	21.08	18.93	35.06	30.67
Additional energy generated (MU)	30.36	18.62	16.71	30.95	27.08
Additional energy (%)	5.22	4.35	3.66	10.61	5.43

5.6. ISSUES AND BENEFITS AFTER RENOVATION

- Pumped storage plants are to meet the peak-power requirements of the power system. Thus, the availability of additional peak power for a longer duration on daily basis will certainly improve distribution power quality and reduce peak shaving which is a definite advantage.
- In a power system, one of the operational benefits of pumped storage scheme shall be reduction of carbon emission. By using variable speed machines, additional energy due to higher efficiency to the tune of 30.36 MU shall be

available. This additional energy is equivalent to reduction of carbon by an amount of 23,073.6 tCo_2 (Calculated based on Central Electricity Authority - CO_2 Baseline Database for the Indian Power Sector, January 2013).

- The variable speed pumped storage plant in a power system can be utilized to balance power fluctuations from RES both in pumping and generating mode [96]. Since, Tamil Nadu has large wind energy installations (> 7000 MW), the renovation of Kadamparai with variable speed drives will be more beneficial to the state grid.
- The power electronic converters which are necessary for variable speed operation create high harmonics. This can be eliminated by using suitable active harmonic filters. The Tamil Nadu state grid already has vast experience of power quality management since the large wind energy installations of the state are equipped with induction generators. The harmonics from the induction generators have been filtered by suitable harmonic filters connected at the interconnection to the system. Similarly, the harmonics need to be managed in the case of Kadamparai also.
- Further, the results of the variable speed operation have been compared with the results of the water regulation model and are shown in the following Table 5.4.

Table 5.4 Comparison of results

(Water regulation model and variable speed analysis)

Year	Results from water regulation model	Results from variable speed analysis
	Spill occurred after simulation (Mcft)	Additional water can be pumped by VSD (Mcft)
2006	0	1214.32
2007	736.46	744.60
2008	368.75	668.51
2009	633.66	1238.18
2010	116.49	1083.13

From the above table, it can be concluded that spill can be efficiently reduced by using variable speed operation.

5.7. CONCLUSION

The analysis reveals that it is possible to operate the plant beneficially by adopting variable speed machines. The 400 MW synchronous machines at Kadamparai are in working condition, which can be converted to variable speed machines by introducing static frequency converters or by total replacement with DFIG. This paper mainly analyzes the possibilities of conversion of existing station by variable speed machines by studying the impact on cycle conversion efficiency and the benefits derived. It is recommended to choose variable speed technology machine while planning for renovation and modernization for Kadamparai pumped storage power plant in future from the following reasons:

1) Possibility of increased efficiency in turbine mode and part load operation in pump mode using variable speed technology.

2) With the grid frequency approaching 50 Hz and for frequency regulated operation, variable speed machine with better control system would be beneficial for operation of pumped storage station. Further when the surplus power available in the grid even about 70% to 90% of the machine capacity, the station could use such power to store water for subsequent use in generation.

3) Adopting equal capacity SFC to the unit rating for each of the existing synchronous machines or separate SFC with 20% to 30% of the unit rating for each of the units with individual DFIG units has to be decided on techno-economic criteria. It is needless to state that individual DFIG machines have got more operational benefits and occupies less space.

In conclusion, it may be inferred that while undertaking the renovation and modernization of Kadamparai pumped storage power plant, it would be desirable to arrive at the decision of whether to use existing generators with renovation and corresponding capacity SFC or DFIG involving new generating equipment on the basis of economic benefits.

The following chapter analyzes the economics of Kadamparai pumped storage plant.

Chapter 6

ECONOMIC ANALYSIS OF KADAMPARAI PUMPED STORAGE PLANT

6.1. INTRODUCTION

This chapter analyzes the economics of Kadamparai pumped storage plant. Various costs involved in pumped storage operation in Indian context are already analyzed in Chapter - 2. The Kadamparai plant is operated as per the requirement of the state power system and cost of expenditure is met by the controlling authority i.e. TANGEDCO. Cost of energy is the average revenue sale from power production of the state and no separate cost pattern is adopted for pumping energy consumption since it is deducted from electricity board account as other expenditure (Annexure – 12). In this context the analysis of economic aspect of Kadamparai plant and results would be useful for investors and researchers to understand the economics of Indian pumped storage schemes.

6.2. ECONOMIC ASPECTS OF KPSP

The decision variables such as the annual energy generation (MU), annual pump energy consumption (MU), the energy cost for pumping and generation (Rs./kWh) are used to calculate the gain. The 20% annual fixed charges (AFC) assumed in the calculation towards expenditure is equal to the approved rate by the state regulatory authority (Annexure – 13). Transmission losses are not considered in the analysis and in all cases it is assumed as accounted on distribution company account. Cycle efficiency is assumed as 75% [101]. Auxiliary consumption is taken as 0.7% [101]. The cost for other benefits such as VAR regulation etc has not been considered in this analysis with the absence of data and less operation from PHES.

With the above assumptions, the economic benefits of KPSP has been computed based on the following formula,

Annual net benefit, (C) = (Gen x Cost1) – (Pump x Cost2) – AFC (1)

Where,

C = Net benefit in Rs.

Gen = Net generation (Generation from natural inflow, wind, pumping except auxiliary power consumption) in MU.

Cost1 = Cost of power generation in Rs. /kWh.

Pump = Net pump consumption in MU.

Cost2 = Cost of pumping energy in Rs. /kWh

AFC = Annual fixed cost i.e. 20% of capital investment

By using the above formula (1) the net benefit of KPSP has been computed with the following assumptions.

State average revenue on sale of energy is adopted as generation cost (Annexure – 14, 15), annual fixed charge as expenditure. Energy cost of state thermal plants i.e. Rs.1.31/kWh (Annexure – 16) and purchase price of wind energy i.e. Rs. 2.70/kWh [103] which have been adopted for calculating the cost of pumping energy.

The annual net benefit of KPSP for the years 2002-03 to 2011-12 is shown in the following Figure 6.1 (refer Annexure – 17).

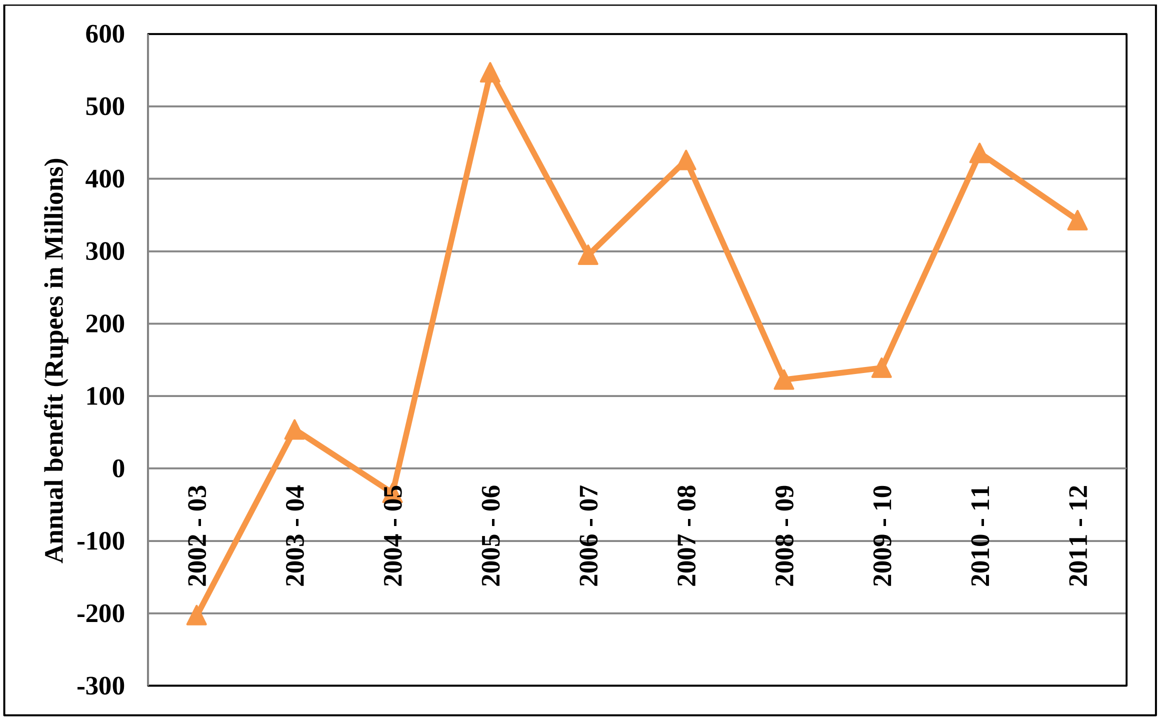
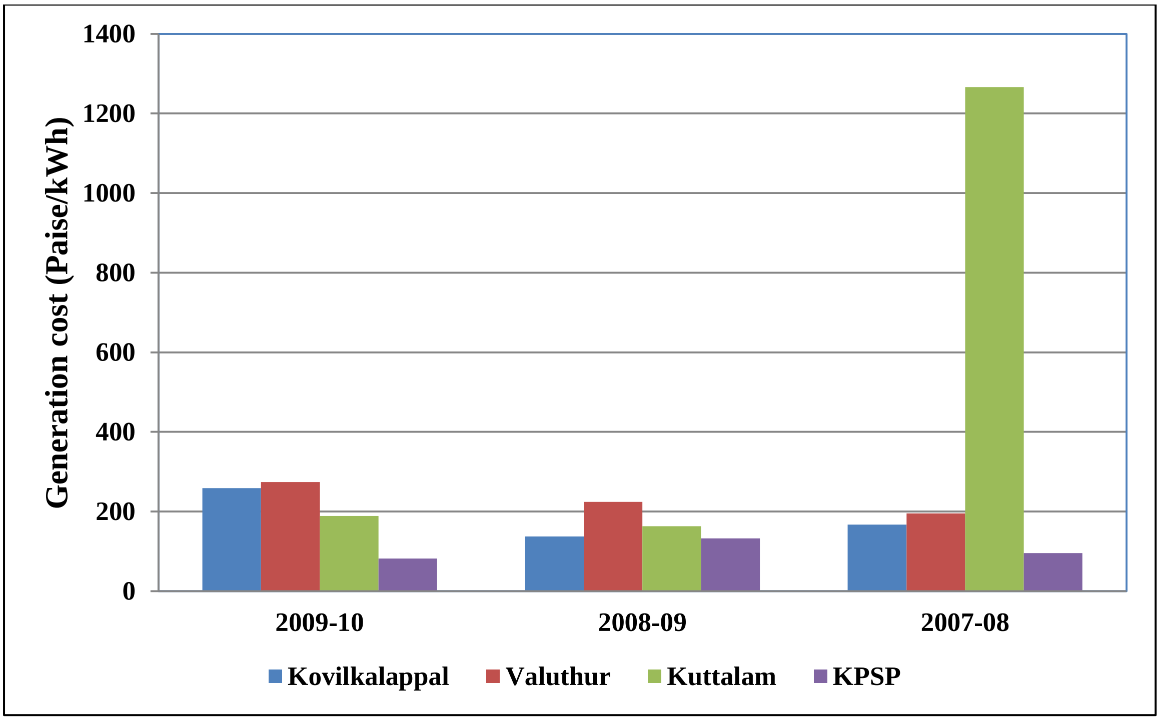


Figure 6.1 Annual benefit of KPSP

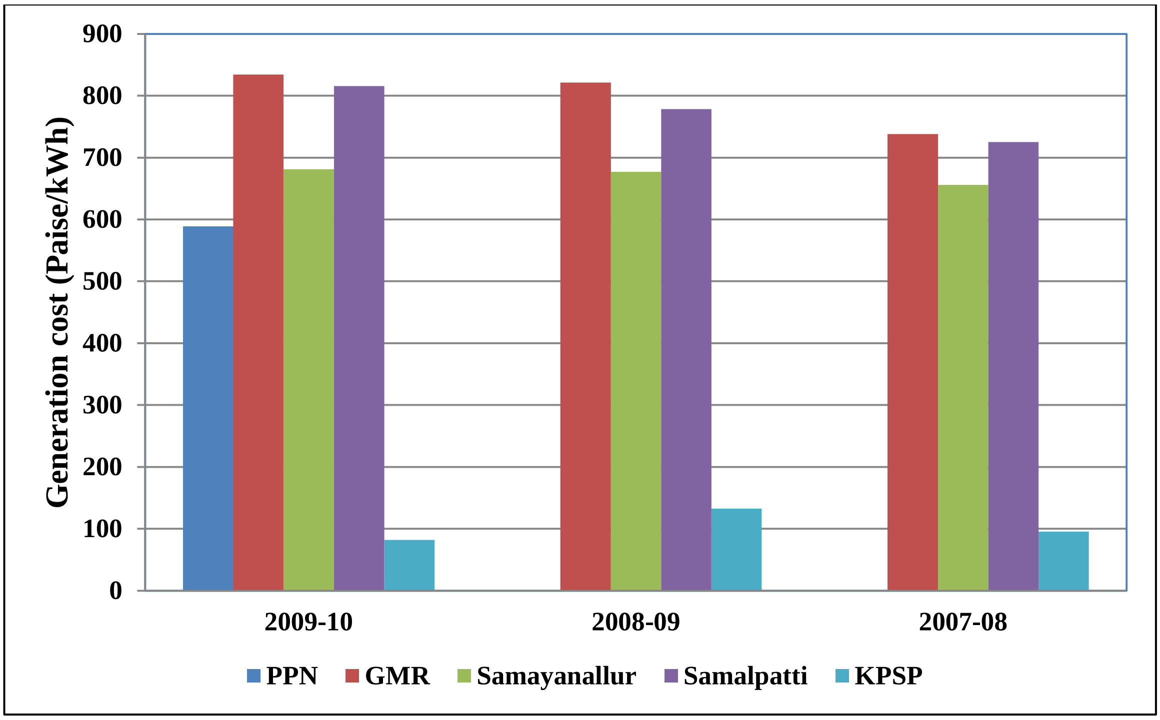
6.3. COMPARISON BETWEEN GAS, DIESEL AND PUMPED STORAGE POWER PLANTS OF TAMIL NADU STATE

The major problem of the Indian power system is the ever increasing peak power demand in almost all the regions. To meet the existing peak demand, Government of India has proposed gas peaking plants in 12th and 13th plan period because of their low capital costs and less construction period in comparison to the pumped storage projects [31]. Further, the running cost of gas plant is based on the price of gas, which is always having a rising tendency. PHES are used for absorbing surplus energy during off peak hours and this facility is not available with gas turbine stations. The gas turbines are used as reserve plants, and operations are considered as a last resource on merit order dispatch due to high production cost [31]. The cost of production with the existing operating conditions of pumped storage has been compared with the cost of gas and diesel power plants which are mainly used for peaking purpose in Tamil Nadu state are as shown Figures 6.2 and 6.3. The generation cost of the KPSP is comparatively less in all the given years.



Source: CEA

Figure 6.2 Actual generation cost for gas power plants in Tamil Nadu state & KPSP



Source: CEA

Figure 6.3 Actual generation cost for diesel power plants in Tamil Nadu state & KPSP

6.4. CONCLUSION

In India, PHES have been developed based on geographical and topographical conditions and the needs of the power system. Developed nations have fixed the cost of pumped storage energy based on electricity trading since they have energy arbitrage opportunities and separate tariff policies. But such commercial policies have not been adopted in India since it is in developing stage. Further, the power trading exists for the previous 6 to 7 years in India and fixing energy pricing has got certain limitation in day to day operation.

At present, PHES are mainly operated to maintain the power system reliability of the country and gradual performance improvement is found from six PHES which are operating in pumping mode after the introduction of ABT. The results of this study reveal that the operation of PHES is found beneficial not only in meeting the peak demand but also economically justifiable (even after considering the cost of pumping energy in the post 2003 scenario). Further, this study reveals that the energy cost of PHES is less when compared with that from other peak generating plants i.e. gas, diesel power plants.

Chapter 7
CONCLUSIONS

7.1. INTRODUCTION

In India, peak and energy shortage are of the order of 4.5% and 4.2% respectively as on 2014, though the installed capacity increased from 2000 MW (1950) to 243 GW (2014) along with new infrastructure on transmission system and formation of national grid. Since energy demand grows incrementally due to the rapid growth of industrial activities, agriculture, etc. it becomes increasingly difficult to bridge the gap between demand and supply. To manage the situation, though capacity addition is being made every year, load shedding is inevitable till date.

The percentage of energy storage schemes, particularly pumped storage schemes determine the stability of any power system. In India, the installed capacity of the PHES represents about 1.98% of the total installed capacity of the country. In this scenario, this research is set to analyze the performance of the existing pumped storage plants in India and specifically analyze the performance of Kadamparai pumped storage plant based on the historical performance and suggest ways and means to improve its performance.

7.2. CONCLUDING REMARKS

The major outcomes of the study are stated below.

1. This study reveals that the reasons for less pumping operation for the stations which are operated on both modes were mainly due to deficit of surplus energy availability in the power system. But this situation has changed gradually and the record shows that the production of some major stations have attained about 50% to 60% of the designed energy generation after 2003. More hours of pumping operation has been observed from the major plants due to formation of the national grid and introduction of ABT. The generation gap observed from the analysis clearly indicates that there is a scope for longer hours of pumping operation in future due to addition of new generating plants along with renewable energy development and regional transfer of surplus power.

2. The technical benefits obtained from the major PHES suggest commissioning of more PHES being helpful to improve the power system stability.

3. Utilizing the hydro power plant sites effectively which are suitable for PHES installation would suit to the country's energy and economic policy.

4. Further, the results of the economic analysis of Kadamparai pumped storage plant operation reveal that the operation of PHES was found beneficial and the production cost of energy from PHES is less compared to other peaking (diesel, gas) power plants.

5. Worldwide, energy storage schemes play a vital role for effective utilization of energy produced from renewable energy sources. The same was experienced from the historical operation of Kadamparai pumped storage plant. The grid rejected wind energy had been utilized by KPSP and which had contributed more pumping operation. Hence the plant performance increased considerably after the period 2008-2009, which is detailed in Chapter – 3.

6. Hence, in India, developing more PHES in future will be helpful to meet the ever increasing peak shortage, improve power system reliability and for better utilization of the renewable energy in optimal way.

7. A reservoir regulation model has been developed to analyze the possibility of improving the present performance of the Kadamparai pumped storage plant. The results obtained show that by maintaining a lesser storage on both reservoirs would give more benefits in utilizing the spill water than maintaining the storage very near to the full reservoir level.

8. As a technological improvement, variable speed operation has been analyzed for improving the plant performance. Use of variable speed machines instead of synchronous machines has been analyzed with historical operational data in both the modes. The analysis reveals that an additional energy output of 25 MU per annum on average could be generated if variable speed machines are adopted in place of existing fixed speed machines. Further the surplus power available is of the order of 70 - 90% of the machine capacity which could also be utilized to recycle the water by using variable speed machines.

9. Since the machines have been run for more than 1,13,620 hours (up to 2012) from the date of commissioning, it is suggested while undertaking the renovation and modernization it would be desirable to go for variable speed machines for obtaining higher operational efficiency than the fixed speed machines.

7.3. FUTURE SCOPE

- Detailed study on economic benefits including other technical constraints in the proposed variable speed conversion of Kadamparai pumped storage plant can be carried out as a future study.
- Further research is necessary to assess the impact of climate change on storage in future and as well as on operation of Kadamparai pumped storage plant. This study may be extended to other pumped storage plants as well.

BIBLIOGRAPHY

[1] Annual report 2009 – 2010, Central Electricity Authority (CEA) [Online]. Available: http://www.cea.nic.in/reports/yearly/annual_rep/2009-10/ar_09_10.pdf

[2] Annual Report 2011-2012 on the Working of State Power Utilities & Electricity Departments, Planning Commission of India [Online]. Available: http://planningcommission.nic.in/reports/genrep/arep_seb11_12.pdf

[3] Annual report 2011-2012, Ministry for New and Renewable Energy sources, Government of India [Online]. Available: http://mnre.gov.in/file-manager/annual-report/2011-2012/EN/index.htm

[4] Annual Reports: 1997 – 98 to 2009 - 10, National Electricity Plan, Vol. 1 (Generation), Load generation balance report 2011-12, Central Electricity Authority (CEA) [Online]. Available: www.cea.nic.in

[5] Annual Reports: 2004 – 05 to 2011 – 12, Southern Regional Load Despatch Centre (SRLDC) [Online]. Available: www.srldc.org

[6] Anonymous, "Kadamparai: India's first pumped-storage plant," *Water power & Dam Construction*, pp. 13 - 18, 1989.

[7] Arunkumar. R., Jothiprakash. V., "Optimal Reservoir Operation for Hydropower Generation using Non-linear Programming Model," *Journal of The Institution of Engineers (India): Series A*, vol. 93, pp. 111-120, 2012.

[8] Baker. J., "New technology and possible advances in energy storage," *Energy Policy*, vol. 36, pp. 4368-4373, 2008.

[9] Beaudin. M., Zareipour. H., Schellenberglabe. A, Rosehart. W., "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy for Sustainable Development*, vol. 14, pp. 302-314, 2010.

[10] Bendl. J., Chomit. M., Schreier. L., "Adjustable-Speed Operation Of Doubly Fed Machines In Pumped Storage Power Plants," in *Ninth International Conf. on Machines and Drives*, pp. 223 – 227, 1999.

[11] Bhanu. B, Roy. A, Pentayya. P., "The Indian medicine," in *IEEE Power Engineering Society General Meeting*, vol.2, pp. 2336-2339, 2004.

[12] Bhide. A., Monroy. C.R., "Energy poverty: A special focus on energy poverty in India and renewable energy technologies," *Renewable and Sustainable Energy Reviews,* vol. 15, pp. 1057-1066, 2011.

[13] Bo Yang, Yuri Makarov, John Desteese, Vilayanur Viswanathan, Preben Nyeng, Bart McManus, John Pease, "On the Use of Energy Storage Technologies for Regulation Services in Electric Power Systems with Significant Penetration of Wind Energy," presented at the 5th International Conference on European Electricity Market, EEM , 2008.

[14] Bocquel. A., Janning J., "Analysis of a 300 MW Variable Speed Drive for Pump-Storage Plant Applications," in *EPE Conference*, Dresden, Germany, 2005.

[15] Carlin. P.W., Laxson. A.S., Muljadi. E.B. The History and State of the Art of Variable-Speed Wind Turbine Technology [Online]. Available: http://www.nrel.gov/docs/fy01osti/28607.pdf

[16] Chang. L.C., "Guiding rational reservoir flood operation using penalty-type genetic algorithm," *Journal of Hydrology,* vol. 354, pp. 65-74, 2008.

[17] Chen. L., McPhee. J., Yeh. W.W.G., "A diversified multiobjective GA for optimizing reservoir rule curves," *Advances in Water Resources,* vol. 30, pp. 1082-1093, 2007.

[18] Connolly. D, Lund. D., Finn. P, Mathiesen. B.V., Leahy. M., "Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage," *Energy Policy,* vol. 39, pp. 4189-4196, 2011.

[19] Daniel Fayolle, Sylvain Lafon. Variable speed applied to hydroelectric schemes history of a technology and to-day’s state of art [Online]. Available: www.power-consulting-associates.com

[20] Data card (as on 01-04-2012), TNEB limited, Tamilnadu generation and Distribution Corporation limited, Tamilnadu Transmission Corporation limited [Online]. Available: http://www.tangedco.gov.in/linkpdf/DataHandBook.pdf

[21] Deane. J.P., Gallachóir. B.P.O., McKeogh. E.J., "Techno-economic review of existing and new pumped hydro energy storage plant," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 1293-1302, 2010.

[22] Dell. R.M., Rand. D.A.J., "Energy storage — a key technology for global energy sustainability," *Journal of Power Sources*, vol. 100, pp. 2-17, 2001.

[23] Determination of Tariff for Generation and Distribution, Tamil Nadu Electricity Regulatory Commission, Order No. 1 of 2012 dated 30-03-2012 (effective from 01-04-2012) [Online]. Available: http://www.tangedco.gov.in/linkpdf/T.ONo.1.pdf

[24] Dicorato. M., Forte. G., Trovato. M., Caruso. E., "Risk-Constrained Profit Maximization in Day-Ahead Electricity Market," *IEEE Transactions on Power Systems*, vol. 24, pp. 1107-1114, 2009.

[25] Doujak. E., Modular Concept For Decentraliced Pump Storage Systems A Small Hydro Approach, *in 14th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, ISROMAC-14,* February 27th - March 2nd, 2012, Honolulu, HI, USA.

[26] Draft report of the expert committee on integrated energy policy, Planning commission, Government of India [Online]. Available: http://planningcommission.nic.in/reports/genrep/intengpol.pdf

[27] Dudhani. S, Sinha. A.K., Inamdar. S.S, "Renewable energy sources for peak load demand management in India," *International Journal of Electrical Power & Energy Systems*, vol. 28, pp. 396-400, 2006.

[28] Eleventh Five Year Plan: 2007-12, Planning Commission, Government of India [Online].Available:http://planningcommission.nic.in/plans/planrel/fiveyr/11th/11_v3/11th_vol3.pdf

[29] *Energy overview*. Available: http://www.energymanagertraining.com /overview/Energy_overview.pdf

[30] Energy statistics 2013, statistics office, National Statistical Organisation, Ministry of Statistics and Programme Implementation, Government of India [Online]. Available: http://mospi.nic.in/mospi_new/upload/Energy_Statistics_2013.pdf

[31] Explanatory Memorandum to the Draft Amendments to the Central Electricity Regulatory Commission (Terms and Conditions of Tariff) Regulations, 2009 [Online].Available: http://cercind.gov.in/2010/Whats-New/Explanatory_Memo.pdf

[32] Fink. A.K, "Tehri Hydro Power Complex on the Bhagirathi River in India," *Hydrotechnical Construction*, vol. 34, pp. 479 - 484, 2000.

[33] Furuya. S., Taguchi. T., Kusunoki. K., Anagisawa. T.Y., Kageyama. T., Kana. T., "Successful Achievement in a Variable Speed Pumped Storage Power System at Yagisawa Power Plant," in *Power Conversion Conference Yokohama*, pp. 603 – 608, 1993.

[34] Gabriel Dan Ciocan, Olivier Teller, Francois Czerwinski, "Variable speed pump-turbines technology," *U.P.B. Sci. Bull.,* vol. 74, pp. 33 - 42, 2012.

[35] Gautam. U.K., Das. D, Chelliah. T.R., "Benefits of variable speed operation: Tehri pumped storage scheme (India) – A case study," in *17th Intern Seminar on Hydropower Plants – Pumped Storage in the Context of Renewable Energy Supply*, Vienna, 2012.

[36] Geetha. T., Jayashankar. V., "Sizing pumped storage in an ABT regime," in *International Power Engineering Conference, IPEC*, pp. 994-999, 2007.

[37] *Global energy observatory web*. Available: http://globalenergyobservatory.org/geoid/2334

[38] Grotenberg. K., Kotch. F., Erlich. I., Bachmann. U., "Modeling and dynamic simulation of variable speed pumped storage units incorporated in the German electric power system," in *9th European conference on power electronics and applications-EPE'09*, Graz, Austria, 2009.

[39] Gupta. S.K., Ankur Panwar, "Pumped storage projects – Relevance and future," in *India Hydro,* New Delhi, pp. 234 – 244, 2005.

[40] Hadjipaschalis. I., Poullikkas. A., Efthimiou. V., "Overview of current and future energy storage technologies for electric power applications," *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 1513-1522, 2009.

[41] Hassan Hosseini. S.M., Semsar. M.R., Afjei. S.E., A Novel Control Method of Variable Speed Pumped Storage Power Plant, *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE),* vol. 6, Issue 5, pp. 58-6, Jul-Aug 2013.

[42] He. W., "A simulation model for evaluating Tianhuangping pumped storage hydro-plant," *Renewable Energy,* vol. 11, pp. 263-266, 1997.

[43] Hydro development plan for 12th five year plan (2012-2017), Hydro Planning & Investigation Division, Central Electricity Authority, New Delhi, September 2008.

[44] Hydro Potential [Online]. Available: www.npti.in/Download/Hydro/Hydro%20Potential.doc

[45] Ibrahim. H., Ilinca. A., Perron. J., "Energy storage systems—Characteristics and comparisons," *Renewable and Sustainable Energy Reviews,* vol. 12, pp. 1221-1250, 2008.

[46] Ikudo. A., "Optimizing pumped storage hydro facility operation under uncertainty," Department of Industrial, Welding and Systems Engineering, The Ohio State University, 2009.

[47] Janning. J., Schwery. A., "Next generation variable speed pump-storage power stations," in *13th European Conference on Power Electronics and Applications EPE '09,* pp. 1 – 10, 2009.

[48] Jean-Jacques Simond, Alain Sapin, Daniel Schafer. Expected benefits of adjustable speed pumped storage in the European network [Online]. Available: http://infoscience.epfl.ch/record/134070/files/eboaspsiten.pdf

[49] Jen-Kuang. L., Ying. L., Wen-Lung. H., Wen-Shiow. K., "Modeling and Dynamic Simulations of Doubly Fed Adjustable-Speed Pumped Storage Units," *IEEE Transactions on Energy Conversion,* vol. 22, pp. 250-258, 2007.

[50] Jha. D.K., Yorino. N., Zoka. Y., Sasaki. Y., Hayashi. Y., Iwata. K., Oe. R., "Penalty Factor Approach of Minimizing Spill in Finding Operating Policy for Reservoir of a Hydropower Plant: A Case of Japan," in *International Conference on Computer and Electrical Engineering, ICCEE,* pp. 3-7, 2008.

[51] Jiri Koutnik, Martin Bruns, Lars Meier, Christophe Nicolet. Pumped Storage - Grid Requirements for Behavior of Large Motor generators And Confirmation Of Compliance Through Simulation [Online]. Available: http://www.powervision-eng.ch/Profile/Publications/pdf/Hydrovision_2011.pdf

[52] Jose. P.C., Role of hydropower development for improving energy mix with reference to India [Online]. Available: http://www.worldenergy.org/documents/congresspapers/376.pdf

[53] Kaldellis. J.K., Zafirakis. D., Kavadias. K., "Techno-economic comparison of energy storage systems for island autonomous electrical networks," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 378-392, 2009.

[54] Kanakasabapathy. P., Swarup. K.S., "Optimal bidding strategy for multi-unit pumped storage plant in pool-based electricity market using evolutionary tristate PSO," in *IEEE International Conference on Sustainable Energy Technologies, ICSET*, pp. 95-100, 2008.

[55] Kerkman. R.J., Lipo. T.A., Newman. W.G., Thirkell. J.E., "An Inquiry into Adjustable Speed Operation of a Pumped Hydro Plant Part 1 - Machine Design and Performance," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-99, pp. 1828-1837, 1980.

[56] Kittredge. C.P., "Centrifugal Pumps Used as Hydraulic Turbines", *Journal for Engineering for Power*, pp. 74 - 78, 1961.

[57] Koji Inoue, Shiro Nagasue, Masayuki Okada, Mikisuke Higuchi, "Renovating of Existing Pumped Storage Power Plant from Conventional System to Adjustable Speed System," in *International Conference on Electrical Machines and Systems ICEMS*, pp. 1642 - 1644, 2010.

[58] Kondoh. J., Ishii. I., Yamaguchi. H., Murata. A., Otani. K., Sakuta. K., Higuchi. N., Sekine. S., Kamimoto. M., "Electrical energy storage systems for energy networks," *Energy Conversion and Management,* vol. 41, pp. 1863-1874, 2000.

[59] Krishnan. K., "Criteria For Installing Pumped Storage Schemes In Indian Context With Reference To Hydro Thermal Mix," *Journal of Irrigation & Power*, pp. 1 - 5, January - March 1995.

[60] Kumar. A., Kumar. K., Kaushik. N, Sharma. S., Mishra. S., "Renewable energy in India: Current status and future potentials," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 2434-2442, 2010.

[61] Kumar. N., Reddy. Y.V.R., Das. D., Padhy. N.P., "Existing transmission charging practices in India: Discouraging for power market," in *IEEE Power Systems Conference and Exposition, PSCE*, pp. 1-7, 2011.

[62] Kuri. B., Li. F., "Valuing emissions from electricity towards a low carbon economy," in *IEEE* Power *Engineering Society General Meeting.* 2005, vol. 1, pp. 53-59, *2005*.

[63] Kuwabara. T., Shibuya. A., Furuta. H., Kita. E., Mitsuhashi. K., "Design and dynamic response characteristics of 400 MW adjustable speed pumped storage unit

for Ohkawachi Power Station," *IEEE Transactions on Energy Conversion*, vol. 11, pp. 376-384, 1996.

[64] Le Blond. S.P., Aggarwal. R.K., Abdulhadi. I.F., Burtf. G.M., "Impact of DFIG windfarms and instrument transformers on transient based protection," in *10th IET International Conference on Developments in Power System Protection, DPSP, Managing the Change*, pp. 1-5, 2010.

[65] Lidgate. D., Ramirez. M., Villaroel. J., Balbas. J.A., Hill. J., "Operational planning for pumped storage power station using heuristic techniques," *International Journal of Electrical Power & Energy Systems*, vol. 4, pp. 111-119, 1982.

[66] Load Generation Balance Report 2011-12, Central Electricity Authority (CEA), Ministry of Power, Government of India.

[67] Loucks. D.P., "Water Resource Systems Models: Their Role in Planning," *Journal of Water Resources Planning and Management*, vol. 118, pp. 214-223, 1992.

[68] Lund. J., Guzman. J., "Derived Operating Rules for Reservoirs in Series or in Parallel," *Journal of Water Resources Planning and Management*, vol. 125, pp. 143-153, 1999.

[69] Manual on pumps used as turbines [Online]. Available: www.dii.unipd.it

[70] McDowall. J.A., "Status and Outlook of the Energy Storage Market," in *IEEE Power Engineering Society General Meeting*, pp. 1-3, 2007.

[71] Mishra. Y., Mishra. S., Fangxing. L., Zhao-Yang. D., Bansal. R.C., "Small-Signal Stability Analysis of a DFIG-Based Wind Power System Under Different Modes of Operation," *IEEE Transactions on Energy Conversion*, vol. 24, pp. 972-982, 2009.

[72] Monthly Report, Central Electricity Authority (CEA) [Online]. Available: http://www.cea.nic.in/reports/monthly/executive_rep/apr12/7.pdf

[73] National Policy for Hydro Power Development [Online]. Available: http://www.nhpcindia.com/writereaddata/English/PDF/hydro-policy.pdf.

[74] Nicolet. C, Pannatier. Y, Kawkabani. B., Schwery. A., Avellan. F, Simond. J.J., "Benefits of Variable Speed Pumped storage Units in Mixed Islanded Power Network during Transient Operation," in *HYDRO 2009, 16th annual Hydro Conference*, Lyon, France, 2009.

[75] Ning. L., Chow. J.H., Desrochers. A.A., "Pumped-storage hydro-turbine bidding strategies in a competitive electricity market," *IEEE Transactions on Power Systems,* vol. 19, pp. 834-841, 2004.

[76] Othman Hassan Abdalla, Minxiao Han, “Power Electronics Converters for Variable Speed Pump Storage”, *International Journal of Power Electronics and Drive System ,IJPEDS, Vol. 3, No. 1, pp. 74 – 82, March 2013.*

[77] *Peak power deficit hits 10-year high*. Available: http://www.business-standard.com/india/news/peak-power-deficit-hits-10-year-high/304466/

[78] Perez. J.I., Wilhelmi. J.R., Maroto. L., "Adjustable speed operation of a hydropower plant associated to an irrigation reservoir," *Energy Conversion and Management,* vol. 49, pp. 2973-2978, 2008.

[79] Public notice, Maharashtra State Power Generation Company Ltd [Online]. Available: http://www.mercindia.org.in/pdf/Order%2058%2042/Pubic_Notice_2_of_2012_Eng.pdf

[80] Quantifying the Value of Hydropower in the Electric Grid: Final Report [Online]. Available: http://www1.eere.energy.gov/water/pdfs/epri_value_hydropower_electric_grid.pdf

[81] Regional Hydro-power Resources: Status of Development and Barriers, United States Agency for International Development Under South Asia, Regional Initiative for Energy Nexant SARI/Energy [Online]. Available: http://pdf.usaid.gov/pdf_docs/PNADA888.pdf

[82] Ridgway. S.L., Dooley. J.L, Hammond. R.P, "Large energy storage systems for utilities," *Applied Energy,* vol. 6, pp. 133-142, 1980.

[83] Salih Fadil, Celal Yasar, "A Pseudo Spot Price Algorithm Applied to the Pumped-Storage Hydraulic Unit Scheduling Problem," *Turkish Journal of Electrical Engineering and Computer Sciences,* vol. 8, 2000.

[84] Schafer. D., Simond. J.J. Advantages of the Electric Grid using a Doubly Fed Asynchronous Machine – Numerical Simulations [Online]. Available: http://infoscience.epfl.ch/record/128546/files/afteguadfamnsHyropower97.pdf

[85] Schafer. D., Simond. J.J. Adjustable speed Asynchronous Machine in Hydro Power Plants and its Advantages for the Electric Grid Stability [Online]. Available: http://infoscience.epfl.ch/record/134078/files/asamihppaiaftegs.pdf

[86] Schainker. R.B., "Executive overview: energy storage options for a sustainable energy future," in *IEEE Power Engineering Society General Meeting*, vol.2, pp. 2309-2314, 2004.

[87] Schoppe. C., "Wind and Pumped-Hydro Power Storage: Determining Optimal Commitment Policies with Knowledge Gradient Non-Parametric Estimation," Department of Operations Research and Financial Engineering, Princeton University, June 2010.

[88] Shenglian. G., Xiang. L., Pan. L., Fuqiang. G., "Optimal Operation of Cascade Hydropower Plants," in *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, pp. 1-4, 2009.

[89] Shrivastava. N.A., Ch. S., Panigrahi. B.K., "Price forecasting using computational intelligence techniques: A comparative analysis," in *International Conference on Energy, Automation, and Signal, ICEAS*, pp. 1-6, 2011.

[90] *Srisailam Pumped Storage Plant Official Web Page*. Available: http://apgenco.gov.in/inner.asp?frm=viewpower&PSId=121&filename=PowerStations.xml&subhname=&pstype=Hydel&Tagname=PowerStations121&hname=SriSailam%20LBHES

[91] Standing Committee on Energy 2005-06 Fourteenth Lok Sabha, Ministry of Power, ‘Hydro Power – A Critique’ [Online]. Available: http://164.100.24.208/ls/CommitteeR/Energy/5rep.pdf

[92] Sule. B.F., "Reservoir operation policies for optimizing energy generation at the Shiroro Dam," *Water Resources Management*, vol. 2, pp. 209-219, 1988.

[93] Sunil K Khosla, Judith Plummer, "How Price Reform Revolutionized The Operational Discipline of India’s Power Sector," *International Journal of Regulation and Governance*, vol. 5, pp. 41 - 59, 2005.

[94] Suresh. S., Kapuscinski. R., Wu. O., "The case for pumped storage units in the Indian electricity sector," *1st International Conference on Electrical Energy Systems, ICEES*, pp. 218-220, 2011.

[95] Suul. J.A. Variable Speed Pumped Storage Hydropower Plants for Integration of Wind Power in Isolated Power Systems [Online]. Available: http://www.intechopen.com/books/renewable-energy/variable-speed-pumped-storage-hydropower-plants-for-integration-of-wind-power-in-isolated-power-syst

[96] Suul. J.A., Uhlen. K., Undeland. T., "Variable speed pumped hydropower for integration of wind energy in isolated grids – case description and control strategies," in *Nordic Workshop on Power and Industrial Electronics, NORPIE 2008*, Espoo, Finland, June, 2008.

[97] Tang. J., Huang. W.V., "Hydrothermal scheduling problems with pumped-storage hydro plants," *Computers & Industrial Engineering,* vol. 23, pp. 129-132, 1992.

[98] Tsung-Ying. L., Nanming. C., "The effect of pumped storage and battery energy storage systems on hydrothermal generation coordination," *IEEE Transactions on Energy Conversion,* vol. 7, pp. 631-637, 1992.

[99] Varma. C.V.J., "Role of Pumped Storage Plants and Its Integration into Power System," *Journal of Irrigation & Power,* pp. 101 - 105, October 1994.

[100] Varma. C.V.J., Rao. A.R.G. "*Pumped storage schemes in India,* Central Board of Irrigation & Power, November, 2007.

[101] Velayutham.A., Kulkarni. S.B., Petition for Approval of Operating Norms for Pumped Storage Stations and Tariff Determination of Ujjani and Paithan Pumped Storage Stations, Hearing from MSPGCL to MERC [Online]. Available: www.mercindia.org.in

[102] Venkateswarlu. N., Velmurugan. M., Udaya Baskar. S., "Evaluating Demand Response of Hydro Plant with Mixed Pumped Storage," *International Journal of Scientific and Research Publications,* vol. 2, pp. 1 - 4, June, 2012.

[103] Venugopal. K. Open Access and Regulatory Issues concerning wind power development in India [Online]. Available: http://static.infraline.com/re/reports/wind/Open%20Access%20and%20Regulatory%20Issues%20concerning%20wind%20power-K%20Venugopal.pdf

[104] Verma. V.K., Batra. S., "A new business model for pumped storage scheme," in *India Hydro,* New Delhi, pp. 227 - 233, 2005.

[105] Vijay L. Sonavane, Raja. V.P., Petition filed by Water Resources Department, Government of Maharashtra (GoMWRD) and Maharashtra State Power Generation Company Limited (MSPGCL) for approval of Lease Rent for Ghatghar Pumped Storage Hydro Power Station operated and maintained by MSPGCL and owned by GoMWRD [Online]. Available: http://www.mercindia.org.in/pdf/Order%2058%2042/Order_2_of_2012_27_Dec_2012.pdf

[106] Wilhelmi. J.R., Fraile Ardanuy. J.J., Fraile Mora. J.J., Inigo. L. Adjustable Speed Hydro Generation [Online]. Available: http://icrepq.com/pdfs/WILHELMI360.pdf

[107] Wurbs. R.A., "Reservoir-System Simulation and Optimization Models," *Journal of Water Resources Planning and Management*, vol. 119, pp. 455-472, 1993.

[108] Yajvender Pal Verma, Ashwani Kumar, "Profit maximization and optimal sizing of renewable energy sources in a hybrid system," *International Journal of Engineering Science and Technology*, vol. 2, pp. 4575 - 4584, 2010.

[109] Yang. C.J., Jackson. R.B., "Opportunities and barriers to pumped-hydro energy storage in the United States," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 839-844, 2011.

[110] Zahraie. B., Hosseini. S.M., "Development of reservoir operation policies considering variable agricultural water demands," *Expert Systems with Applications*, vol. 36, pp. 4980-4987, 2009.

Annexure – 1

Permission letter from TNEB authorities for visiting Kadamparai power house

TAMIL NADU ELECTRICITY BOARD

POWERING TAMILNADU'S PROGRESS

Vigilance Cell
Anna Salai
Chennai – 2.

Memo No. 26261/B11/B111/2010- 1 dt. 17. 09.2010

Sub: Vigilance Cell - Visit to Kadamparai Hydro Power Station by Th.N.Sivakumar, Ph.D., Scholar at Water Resources Development and Management, Indian Institute of Technology, Roorkee - Permission – Granted.

Ref: 1. V.C.Memo No.45728/V.C.8/87-3, dt. 30.3.1988
2. From the Professor (Hydro Electric), Water Resources Development and Management, Indian Institute of Technology, Roorkee Letter dt. 10.09.2010.

--000---

Permission is granted for visiting Kadamparai Hydro Power Station in any two days in the fist week of October 2010 to Thiru.N.Sivakumar, Ph.D. Scholar at Water Resources Development and Management, Indian Institute of Technology, Roorkee in connection with " Techno Economic Evaluation of Pumped Storage Schemes in the Indian Context " subject to the condition that his observations and the study report to be made available to the Board for its use and also on the conditions specified in the Memo first cited.

2. Th.N.Sivakumar is advised to contact Er. Namasivayam, Executive Engineer./Controls/ Kadamparai Power House for his studies and hand over the final copy of thesis for forwarding the same to the C.E./Hydro/ Chennai.

ADDL. DIRECTOR GENERAL OF POLICE/VIGILANCE (A/c)

To
The Superintending Engineer./
Generation Circle/ Kadamparai
Copy to :- Th.N.Sivakumar, Ph.D.,
Thro' Th.Devaduta Das,
Professor (Hydroelectric),
Dept. of Water Resources Development & Management
Indian Institute of Technology, Roorkee
Roorkee – 247 667.

Copy to: The Chief Engineer./Hydro/
Tamil Nadu Electricity Board/ Chennai – 2.

// TRUE COPY // FORWARDED BY ORDER //

SECTION OFFICER 18/9/10

Annexure – 2 [100]

Features of major pumped storage schemes

Sl. No.	Name of PSS	UR	LR	Type of Power House	UR Volume (MCM)	LR Volume (MCM)	Power Evacuation (kV)	Tailrace Tunnel or Channel (m)	Tailrace Tunnel or Channel (m^3)	Rated Head (m)	Speed (RPM)	Year of Commissioned
1.	Kadamparai (400 MW) (4 x 100 MW)	✓	E	Cavern	26.8	-	220	1476 L 7 D	56,774.34	341	500	1987-89
2.	Srisailam (900 MW) (6 x 150 MW)	E	E	Cavern	-	-	400	2300 L 15 D	4,06,237.5	91/95	136.4	2000-03
3.	Ghatghar (250 MW) (2 x 125 MW) (Pure)	✓	✓	Cavern	6.05	3.57	220	425 L 5.8 D	11,223.15	385.6	-	1995-08
4.	Purulia 900 MW (4 x 225 MW) (Pure)	✓	✓	Cavern	13	13	400	590L, 8.7D 590L, 5.6D	49,580.21	177	250	2007-08
5.	Kadana (240 MW) (4 x 60 MW)	✓	UC	Surface	1690	-	220	Short	-	43.5/47	142.85	1990-98
6.	Bhira (150 MW)	✓	✓	Shaft	523.02	1.54	220	70 L 3.9 D	835.7895	480/532	500/750	1995

UR – Upper Reservoir, LR – Lower Reservoir, ✓ - Newly constructed, E - Existed, UC – Under Construction, L – Length, D - Diameter

Annexure - 3

Operational pattern of KPSP – March 2009

Date/Time	1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	G1	0	P1
1	0	P1	0	0	0	0	0	G1	0	P4
2	0		0	0	0	0	0	0	0	P4
3	0	0	0	0	0	0	0	0	0	P4
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	G1	0	0	0
6	0	0	0	0	0	0	G1	0	0	0
7	G1	G1	G2	G2	G2	G1	G2	0	G1	0
8	G1	G1	G2	G2	G2	G2	G2	0	G1	0
9	0	G1	G2	G1	G2	G2	G1	0	0	0
10	0	G2	G2	G1	G2	G2	G1	0	0	0
11	0	G2	G2	G2	G2	G3	G2	0	G1	0
12	0	G2	G2	G2	G2	G3	G1	P2	G1	0
13	0	G1	0	G1	G1	0	G1	0	0	0
14	0	G1	0	G1	0	0	0	0	P1	0
15	0	G1	0	G1	0	0	0	0	0	0
16	0	G1	0	G1	0	0	0	0	0	0
17	0	G2	0	0	0	0	0	0	0	0
18	P2	G1	0	0	0	0	0	P2	P2	P1
19	0	G2	G2	G2	G2	G2	0	0	0	0
20	0	G1	G2	G2	G2	G2	0	0	0	0
21	0	G1	G1	0	G1	G1	0	0	0	P2
22	0	0	0	0	0	G1	G1	0	0	P3
23	0	0	0	0	G1	G1	G1	0	0	P3
24	0	0	0	0	0	G1	G1	0	0	P3

Annexure – 3 (contd.)

Operational pattern of KPSP – March 2009

Date/Time	11	12	13	14	15	16	17	18	19	20
0	P4	P3	0	0	0	P4	P1	0	0	G1
1	P4	P3	P1	0	P2	P4	P2	0	0	0
2	P4	P3	P3	P1	P3	P4	0	0	0	0
3	P4	P3	P4	0	P3	P4	0	0	0	P1
4	P3	P3	P2	0	P1	P4	0	0	0	0
5	0	0	P2	0	0	P4	0	0	G1	G1
6	0	0	0	G1	0	P4	G2	G1	G1	G1
7	0	G1	0	G1	0	G2	G2	G1	G2	G2
8	0	G1	0	G1	0	G2	G2	G1	G1	G2
9	P1	0	0	G1	0	0	G1	G1	0	0
10	P1	P1	0	0	0	0	G2	G1	G4	G3
11	P1	0	0	G1	0	G2	G3	G2	G4	G4
12	P1	0	0	G1	0	G2	G2	G2	G3	G4
13	0	0	G1	G1	0	G2	G2	G2	G1	G2
14	0	0	G1	G1	0	G2	G1	G3	G1	G2
15	0	0	G1	G1	P1	G2	G2	G2	G1	G2
16	P1	P1	G1	P1	P3	G1	G2	G2	G1	G2
17	P3	P1	G1	P1	P3	0	G2	G2	0	0
18	P3	P1	0	P2	P3	0	G2	G2	G2	0
19	0P2	P1	G1	P1	P3	G1	G2	G4	G2	G1
20	P2	0	G1	P1	P3	G1	G2	G2	G1	0
21	P2	0	0	P1	P4	0	G2	G2	G2	0
22	P3	0	0	P1	P4	0	G2	G1	G2	P1
23	P3	0	0	P1	P4	0	G2	G1	G2	0
24	P3	0	0	0	P4	0	G2	G1	G2	0

Annexure – 3 (Contd.)

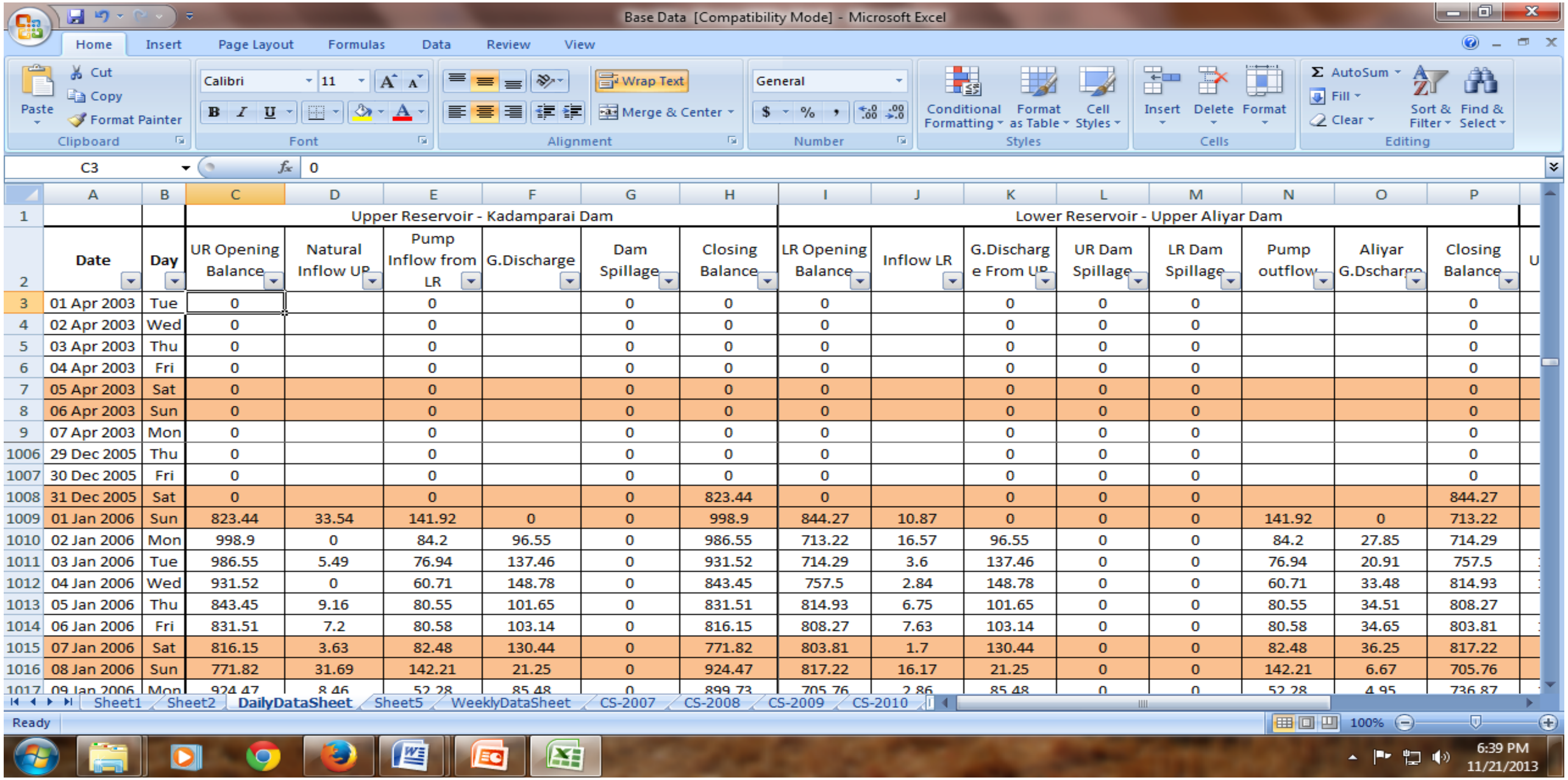
Operational pattern of KPSP – March 2009

Date/Time	21	22	23	24	25	26	27	28	29	30	31
0	P1	0	P4	0	P2	P1	0	P3	0	0	0
1	P1	P1	P4	P2	P2	P1	0	P3	0	0	0
2	P4	P2	P3	P2	P2	P1	P1	P3	0	0	0
3	P4	P2	P3	P2	P2	P2	0	P3	0	0	0
4	P2	P2	P2	P2	P2	P1	0	0	0	0	0
5	0	P2	P2	P2	P1	0	0	0	0	0	G1
6	0	0	G1	G1	0	0	0	0	0	G1	G1
7	0	0	G1	G1	0	0	0	0	0	G2	G2
8	0	0	G1	G1	0	0	0	0	0	G1	G2
9	0	P1	G1	G1	0	0	0	0	0	0	G2
10	P1	P1	G2	0	0	G1	0	0	0	G2	G4
11	P1	P2	G2	0	G1	G1	0	0	0	G2	G4
12	0	P1	G2	G1	G1	G1	0	0	0	G2	G4
13	0	0	G2	G1	0	G1	0	0	0	G1	G3
14	0	P1	G2	G1	0	G1	0	0	0	G1	G3
15	0	P3	G1	G1	0	0	0	0	0	G1	G1
16	0	P3	G1	0	P1	0	P1	0	SCP	G1	0
17	0	P4	0	0	0	0	P2	0	P2	0	0
18	P1	P4	G2	G2	0	0	P2	P1	P2	G1	G2
19	0	P4	G3	G2	G1	0	P2	SCP	P1	G3	G2
20	P1	P4	G3	0	0	0	P3	SCP	0	G3	G2
21	P1	P4	G1	G1	0	0	P3	SCP	0	G2	G1
22	P1	P4	G2	G1	0	0	P3	0	0	G3	G3
23	0	P3	G2	P2	P1	0	P3	0	0	G3	G3
24	0	P3	0	P2	P1	0	P2	0	0	0	0

P – Pump, G – Generator, 1,2,3,4 – Number of units under operation, SCP – Synchronous Condenser Pumping

Annexure – 4

Water regulation model



	Date	Day	Upper Reservoir - Kadamparai Dam						Lower Reservoir - Upper Aliyar Dam							
			UR Opening Balance	Natural Inflow UP	Pump Inflow from LR	G.Discharge	Dam Spillage	Closing Balance	LR Opening Balance	Inflow LR	G.Discharge From UP	UR Dam Spillage	LR Dam Spillage	Pump outflow	Aliyar G.Dscharge	Closing Balance
3	01 Apr 2003	Tue	0		0		0	0	0		0	0	0			0
4	02 Apr 2003	Wed	0		0		0	0	0		0	0	0			0
5	03 Apr 2003	Thu	0		0		0	0	0		0	0	0			0
6	04 Apr 2003	Fri	0		0		0	0	0		0	0	0			0
7	05 Apr 2003	Sat	0		0		0	0	0		0	0	0			0
8	06 Apr 2003	Sun	0		0		0	0	0		0	0	0			0
9	07 Apr 2003	Mon	0		0		0	0	0		0	0	0			0
1006	29 Dec 2005	Thu	0		0		0	0	0		0	0	0			0
1007	30 Dec 2005	Fri	0		0		0	0	0		0	0	0			0
1008	31 Dec 2005	Sat	0		0		0	823.44	0		0	0	0			844.27
1009	01 Jan 2006	Sun	823.44	33.54	141.92	0	0	998.9	844.27	10.87	0	0	0	141.92	0	713.22
1010	02 Jan 2006	Mon	998.9	0	84.2	96.55	0	986.55	713.22	16.57	96.55	0	0	84.2	27.85	714.29
1011	03 Jan 2006	Tue	986.55	5.49	76.94	137.46	0	931.52	714.29	3.6	137.46	0	0	76.94	20.91	757.5
1012	04 Jan 2006	Wed	931.52	0	60.71	148.78	0	843.45	757.5	2.84	148.78	0	0	60.71	33.48	814.93
1013	05 Jan 2006	Thu	843.45	9.16	80.55	101.65	0	831.51	814.93	6.75	101.65	0	0	80.55	34.51	808.27
1014	06 Jan 2006	Fri	831.51	7.2	80.58	103.14	0	816.15	808.27	7.63	103.14	0	0	80.58	34.65	803.81
1015	07 Jan 2006	Sat	816.15	3.63	82.48	130.44	0	771.82	803.81	1.7	130.44	0	0	82.48	36.25	817.22
1016	08 Jan 2006	Sun	771.82	31.69	142.21	21.25	0	924.47	817.22	16.17	21.25	0	0	142.21	6.67	705.76
1017	09 Jan 2006	Mon	924.47	8.46	52.28	85.48	0	899.73	705.76	2.86	85.48	0	0	52.28	4.95	736.87

Annexure – 5

Calculation for energy generation

Kadamparai Power House, G1 (KPH):

1 unit (100 MW) generation 1 hour, Discharge, Q	=	4 Mcft
Energy generation	=	1,000,000 (1 LU)

Upper Aliyar Power House, G2 (UAPH):

1 unit (60 MW) generation, rated discharge	=	600 Q Sec.
Water discharge for 1 hour	=	2.16 Mcft
Energy generation	=	83,000 (0.83 LU)

Generation as per DPR:

The DPR specifies for 8 hours pumping during night and 6 hours generation during day. Calculated for 300 day for a year.

Projected generation by pumping ($400 * 10^3 * 300 / 10^6$)	=	720 MU
Projected generation by natural inflow	=	77 MU
Projected total generation for the year	=	797 MU

Annexure - 6
Variable speed operation of Kadamparai PSP – Generation

Head (m)	Discharge (m^3/sec.)	Rated input (MW)	Input power (MW)	Input power (p.u.)	Synchronous speed (RPM)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed Speed) (%)	Efficiency (variable speed) (%)
395	34	110.914	131.748	1.19	500	88.052	94.768	0.93	85	85
385	34	110.914	128.413	1.16	500	89.188	94.768	0.94	88	88.2
375	34	110.914	125.078	1.13	500	90.370	94.768	0.95	89	89
365	34	110.914	121.742	1.10	500	91.599	94.768	0.97	89	89
355	34	110.914	118.407	1.07	500	92.880	94.768	0.98	89	90
345	34	110.914	115.071	1.04	500	94.217	94.768	0.99	88.2	92
341	34	110.914	113.737	1.03	500	94.768	94.768	1.00	87.8	93
335	34	110.914	111.736	1.01	500	95.613	94.768	1.01	87	93
325	34	110.914	108.401	0.98	500	97.073	94.768	1.02	85.8	91
323	34	110.914	107.733	0.97	500	97.373	94.768	1.03	85	90

Annexure - 7

Variable speed operation of Kadamparai PSP – Pumping (for designed head variation)

Input power = 80 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)
413	80	0.73	86.11	89.66	0.96	83.4	84	16.47	16.59	0.12
393	80	0.73	88.28	89.66	0.98	82.4	84	17.10	17.43	0.33
381	80	0.73	89.66	89.66	1.00	81.2	84	17.38	17.98	0.60
361	80	0.73	92.11	89.66	1.03	80	84	18.07	18.98	0.90
341	80	0.73	94.77	89.66	1.06	80	84	18.75	19.69	0.94

Input power = 90 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)
413	90	0.82	86.11	89.66	0.96	85.5	87.5	18.99	19.44	0.44
393	90	0.82	88.28	89.66	0.98	84.5	87.5	19.73	20.43	0.70
381	90	0.82	89.66	89.66	1.00	84	87.5	20.23	21.07	0.84
361	90	0.82	92.11	89.66	1.03	82.5	87.5	20.97	22.24	1.27
341	90	0.82	94.77	89.66	1.06	81	87.5	21.79	23.54	1.75

Annexure - 7 (contd.)

Variable speed operation of Kadamparai PSP – Pumping (for designed head variation)

Input power = 100 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)
413	100	0.91	86.11	89.66	0.96	87.4	89.4	21.57	22.07	0.49
393	100	0.91	88.28	89.66	0.98	86.2	89.4	22.36	23.19	0.83
381	100	0.91	89.66	89.66	1.00	85.8	89.4	22.96	23.92	0.96
361	100	0.91	92.11	89.66	1.03	84.4	89.4	23.83	25.24	1.41
341	100	0.91	94.77	89.66	1.06	83	89.4	24.81	26.72	1.91

Input power = 110 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)
413	110	1	86.11	89.66	0.96	89	94	24.16	25.52	1.36
393	110	1	88.28	89.66	0.98	88.2	94	25.17	26.82	1.65
381	110	1	89.66	89.66	1.00	87.4	94	25.72	27.66	1.94
361	110	1	92.11	89.66	1.03	86.2	94	26.77	29.20	2.42
341	110	1	94.77	89.66	1.06	85	94	27.95	30.91	2.96

Annexure - 8

Variable speed operation of Kadamparai PSP – Pumping (for operating head variation)

Input Power = 80 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)	New peripheral velocity factor	New speed (rpm)
401	80	0.73	87.39	89.66	0.97	83.2	86.5	16.92	17.59	0.67	0.85	436
391	80	0.73	88.50	89.66	0.99	82.9	86.5	17.29	18.04	0.75	0.85	431
381	80	0.73	89.66	89.66	1.00	81.2	86.5	17.38	18.51	1.13	0.85	425
371	80	0.73	90.86	89.66	1.01	81.5	86.5	17.91	19.01	1.10	0.85	419
361	80	0.73	92.11	89.66	1.03	86.2	86.5	17.71	18.86	0.09	0.85	414

Input Power = 90 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)	New peripheral velocity factor	New speed (rpm)
401	90	0.82	87.39	89.66	0.97	84.9	88.6	19.42	20.27	0.85	0.85	436
391	90	0.82	88.50	89.66	0.99	84.8	88.6	19.90	20.79	0.89	0.85	431
381	90	0.82	89.66	89.66	1.00	84	88.6	20.23	21.33	1.11	0.85	425
371	90	0.82	90.86	89.66	1.01	83.5	88.6	20.65	21.91	1.26	0.85	419
361	90	0.82	92.11	89.66	1.03	82.5	88.6	20.97	22.52	1.55	0.85	414

Annexure – 8 (contd.)

Variable speed operation of Kadamparai PSP – Pumping (for operating head variation)

Input Power = 100 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)	New peripheral velocity factor	New speed (rpm)
401	100	0.91	87.39	89.66	0.97	86.9	94	22.09	23.90	1.80	0.86	441
391	100	0.91	88.50	89.66	0.99	86.5	94	22.55	24.51	1.96	0.86	436
381	100	0.91	89.66	89.66	1.00	85.8	94	22.96	25.15	2.19	0.86	430
371	100	0.91	90.86	89.66	1.01	85.5	94	23.49	25.83	2.34	0.86	424
361	100	0.91	92.11	89.66	1.03	84.4	94	23.83	26.54	2.71	0.86	419

Input Power = 110 MW

Head variation (m)	Input power (MW)	Input power (p.u.)	Peripheral velocity factor	Base peripheral velocity factor	Peripheral velocity factor (p.u.)	Efficiency (fixed speed) (%)	Efficiency (variable speed) (%)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Discharge difference (m^3/sec.)	New peripheral velocity factor	New speed (rpm)
401	110	1	87.39	89.66	0.97	88.3	94	24.69	26.28	6270	0.9	462
391	110	1	88.50	89.66	0.99	87.9	94	25.21	26.96	6710	0.9	456
381	110	1	89.66	89.66	1.00	87.4	94	25.72	27.66	7260	0.9	450
371	110	1	90.86	89.66	1.01	87.2	94	26.36	28.41	7480	0.9	444
361	110	1	92.11	89.66	1.03	86.2	94	26.77	29.20	8580	0.9	438

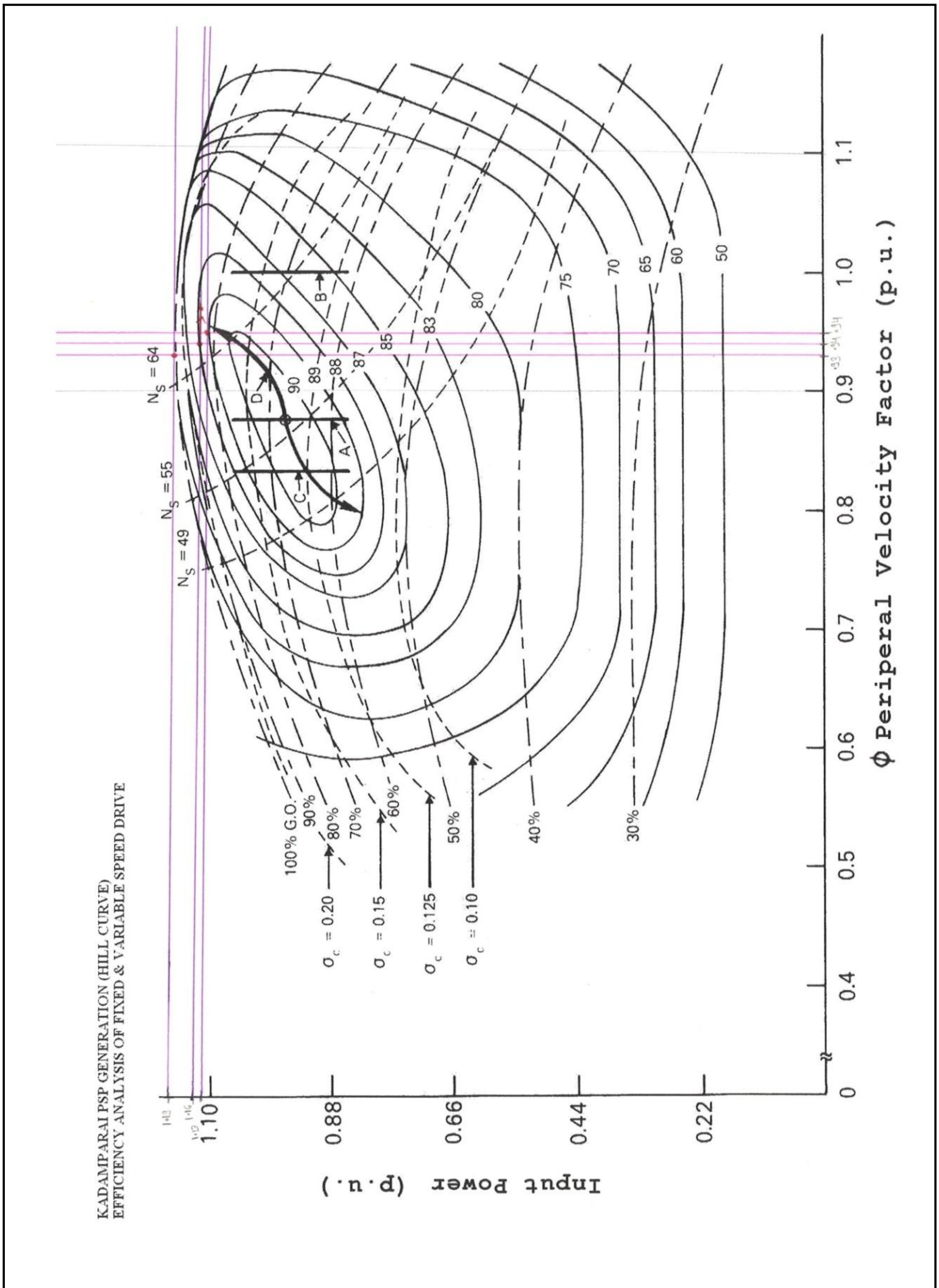
Annexure – 9

Model for calculating pumping benefit for KPSP by using variable speed operation

Date	Day	Pump Discharge (Mcft)	N0. Of Pump units	Pump operating hours	Static head (m)	Friction loss (m)	Dynamic head (m)	Discharge (fixed speed) (m^3/sec.)	Discharge (variable speed) (m^3/sec.)	Total discharge (fixed speed) (MMC)	Total discharge (variable speed) (MMC)	Additional discharge (MMC)
01 Jan 2008	Tue	86.03	3	28.68	377.12	6	383	25.12	25.73	2.59	2.66	0.06
02 Jan 2008	Wed	52.77	2	17.59	381.27	4	385	25.02	28.51	1.58	1.81	0.22
03 Jan 2008	Thu	69.73	3	23.24	381.64	6	388	24.86	28.44	2.08	2.38	0.30
04 Jan 2008	Fri	76.68	3	25.56	381.74	6	388	24.86	28.37	2.29	2.61	0.32
05 Jan 2008	Sat	88.84	3	29.61	382.75	6	389	24.81	28.30	2.65	3.02	0.37
06 Jan 2008	Sun	53.99	2	18.00	386.44	4	390	24.76	28.23	1.60	1.83	0.22
07 Jan 2008	Mon	43.35	2	14.45	387.24	4	391	24.71	28.16	1.29	1.46	0.18
08 Jan 2008	Tue	45.31	2	15.10	387.12	4	391	24.71	28.09	1.34	1.53	0.18
09 Jan 2008	Wed	50.25	2	16.75	385.17	4	389	24.81	28.01	1.50	1.69	0.19
10 Jan 2008	Thu	47.21	2	15.74	376.91	4	381	25.23	27.94	1.43	1.58	0.15
11 Jan 2008	Fri	64.19	3	21.40	377.25	6	383	25.12	27.87	1.94	2.15	0.21
12 Jan 2008	Sat	63.48	3	21.16	377.88	6	384	25.07	27.80	1.91	2.12	0.21
13 Jan 2008	Sun	89.67	3	29.89	378.62	6	385	25.02	27.73	2.69	2.98	0.29
14 Jan 2008	Mon	52.96	2	17.65	377.81	4	382	25.18	27.66	1.60	1.76	0.16
15 Jan 2008	Tue	72.92	3	24.31	377.71	6	384	25.07	27.59	2.19	2.41	0.22

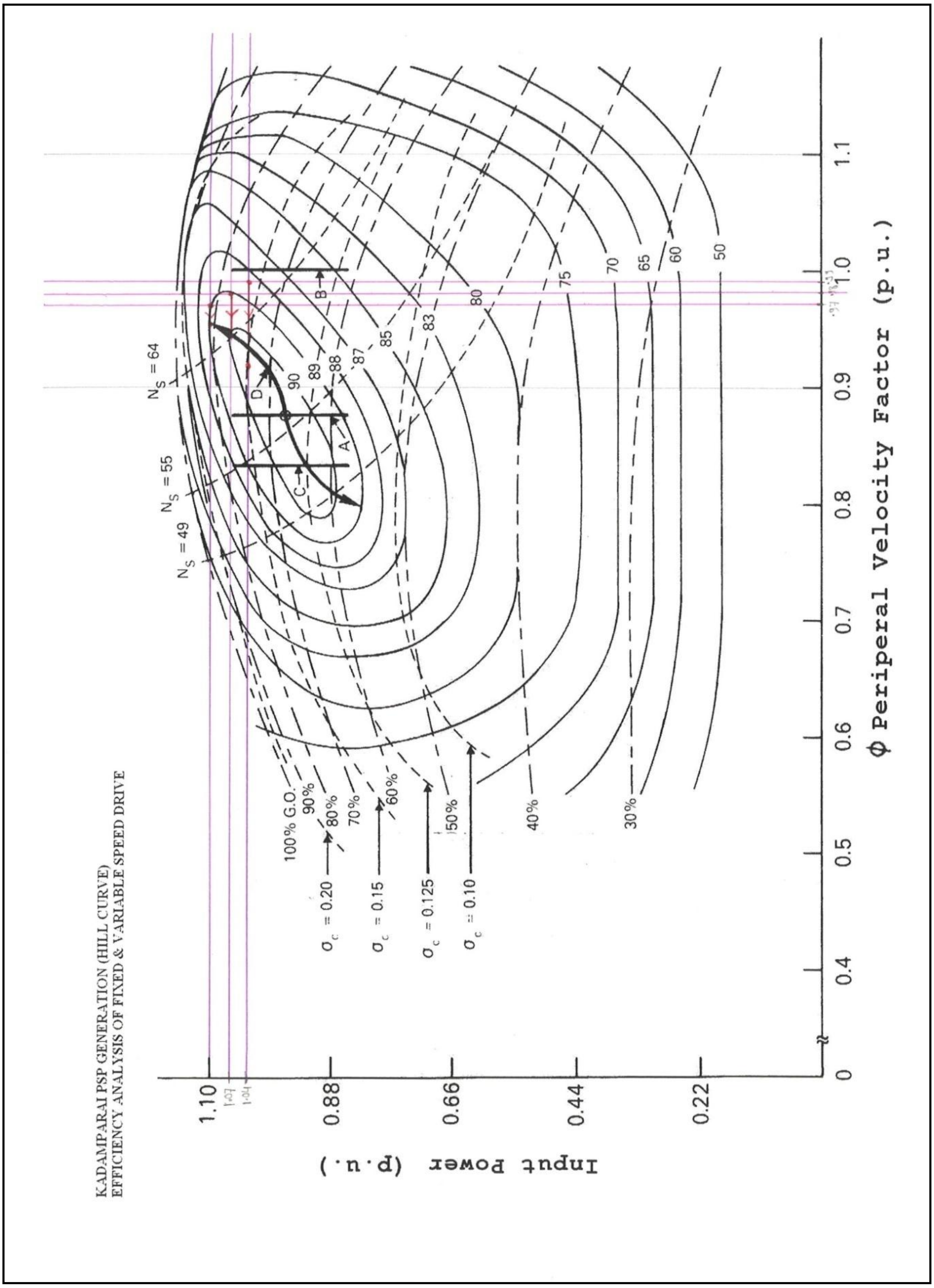
Annexure – 10

Hill curve (Generation)



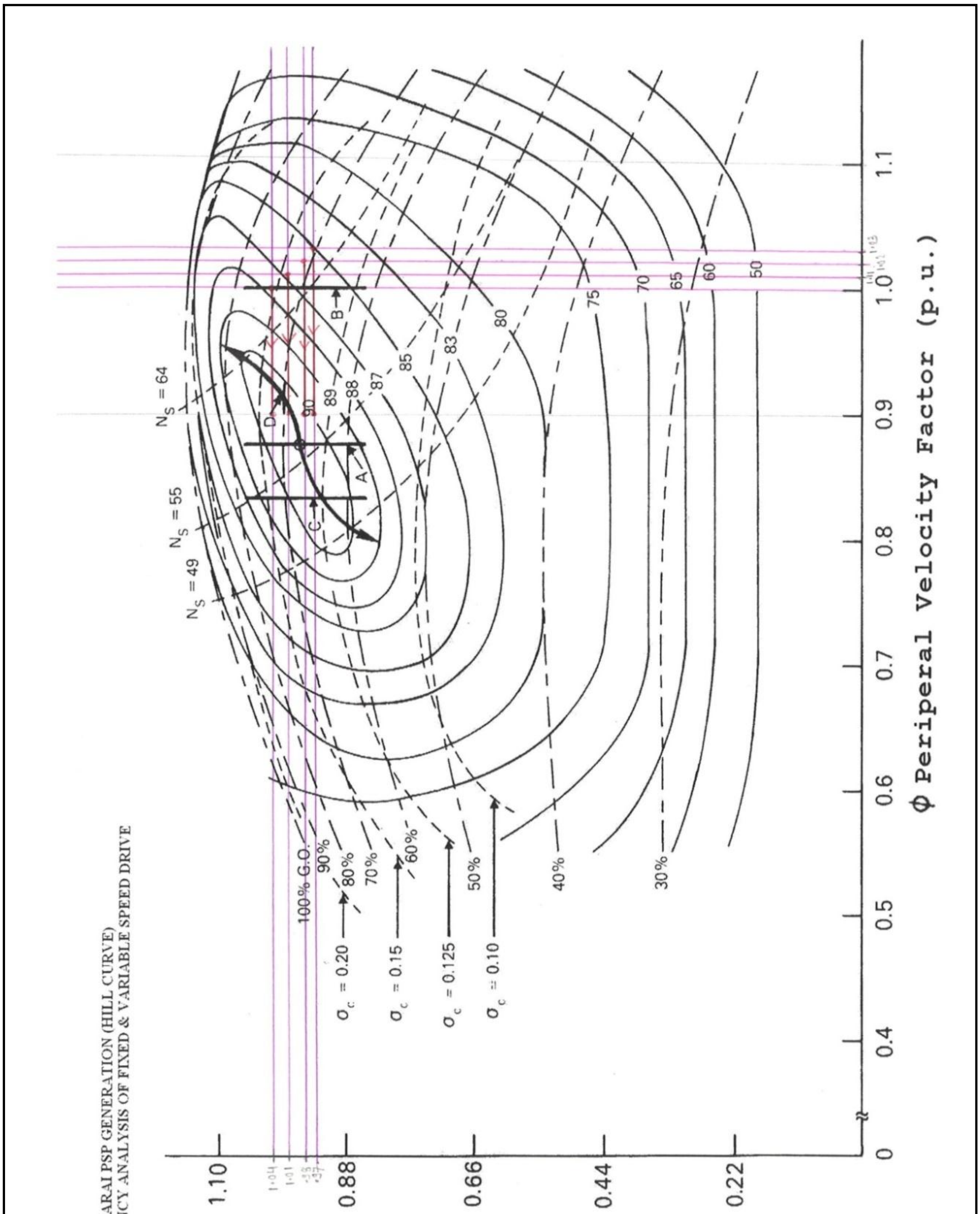
Annexure – 10 (contd.)

Hill curve (Generation)



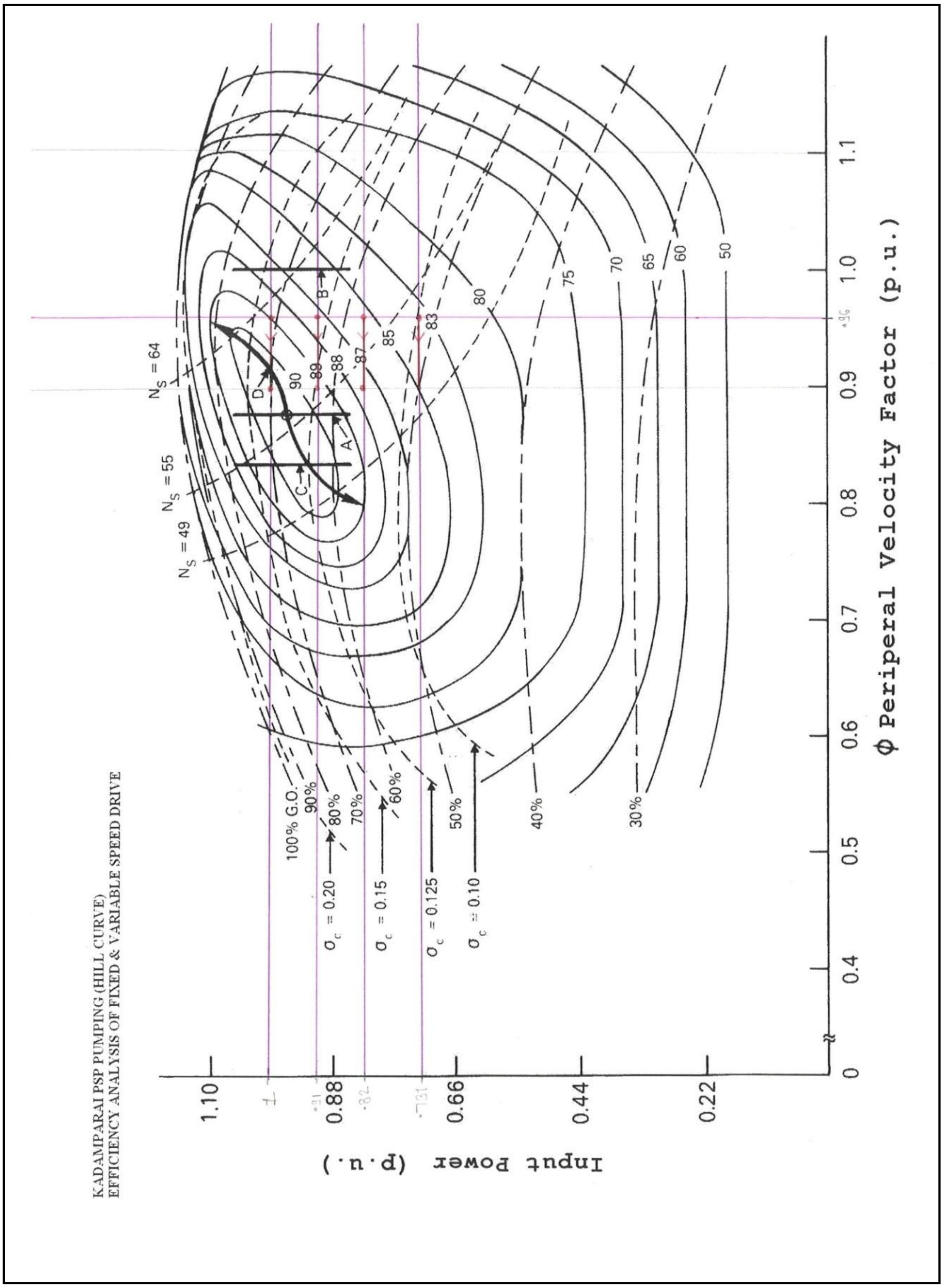
Annexure – 10 (contd.)

Hill curve (Generation)



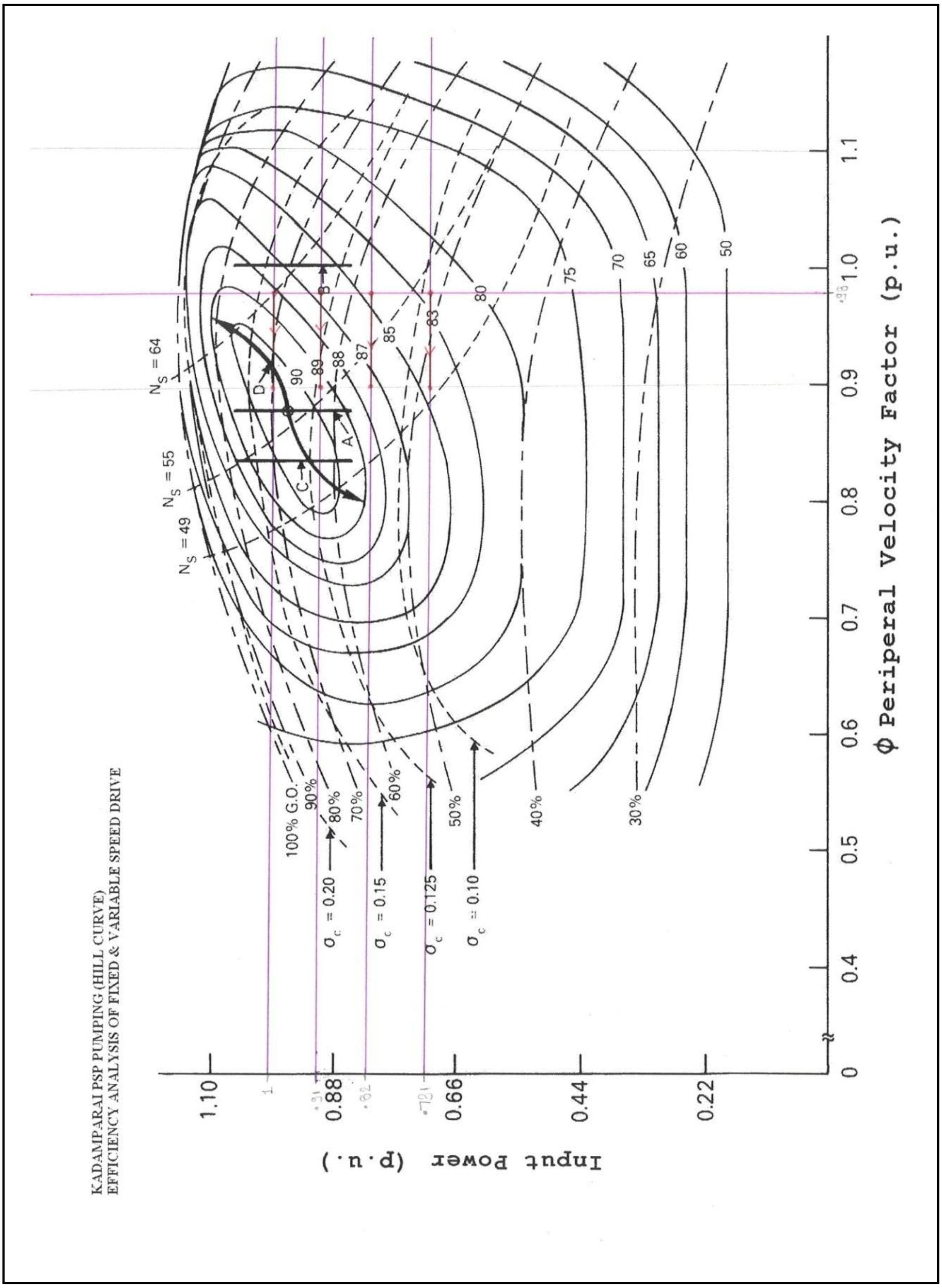
Annexure – 11

Hill curve (Pumping)



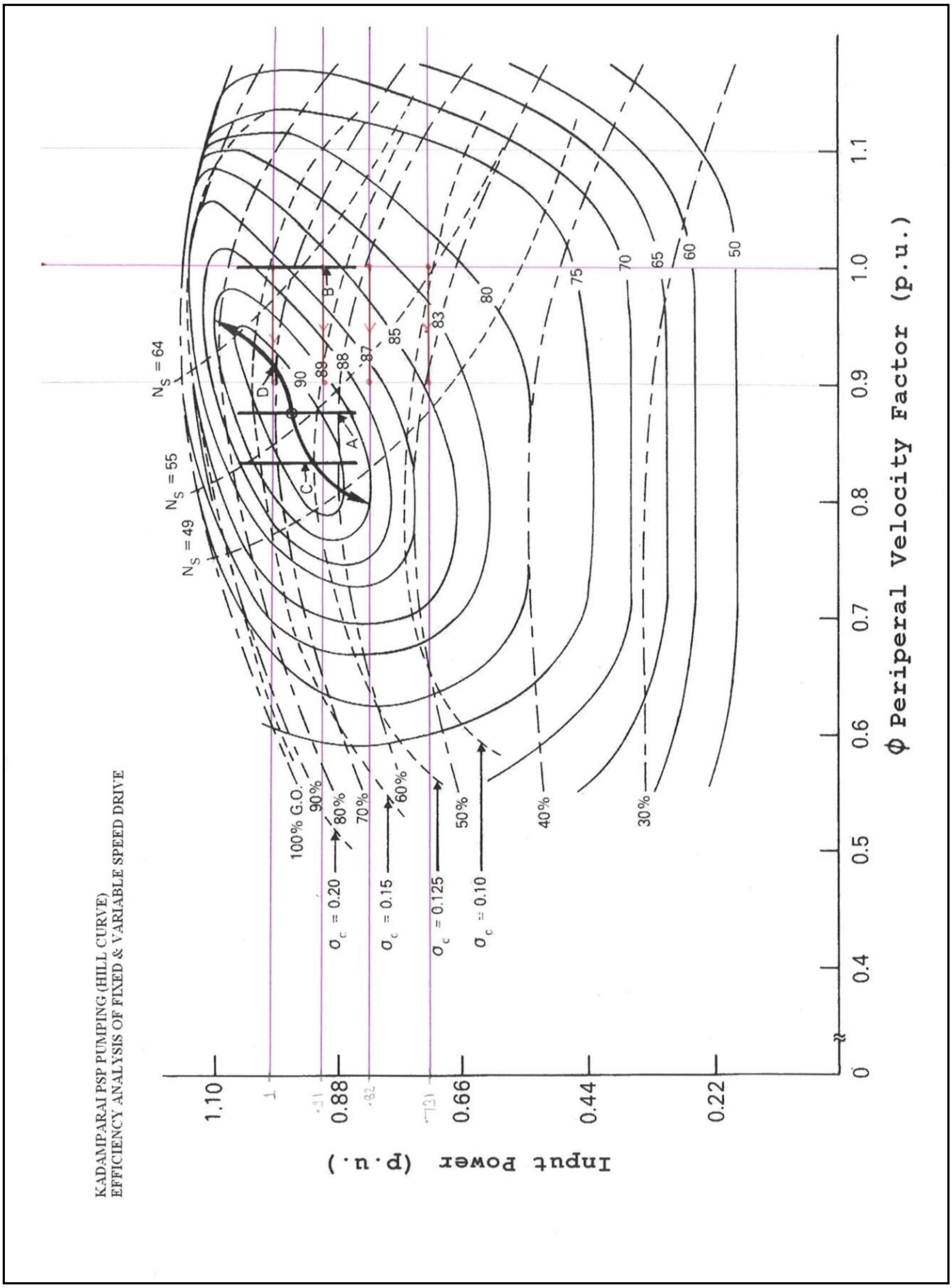
Annexure – 11 (contd.)

Hill curve (Pumping)



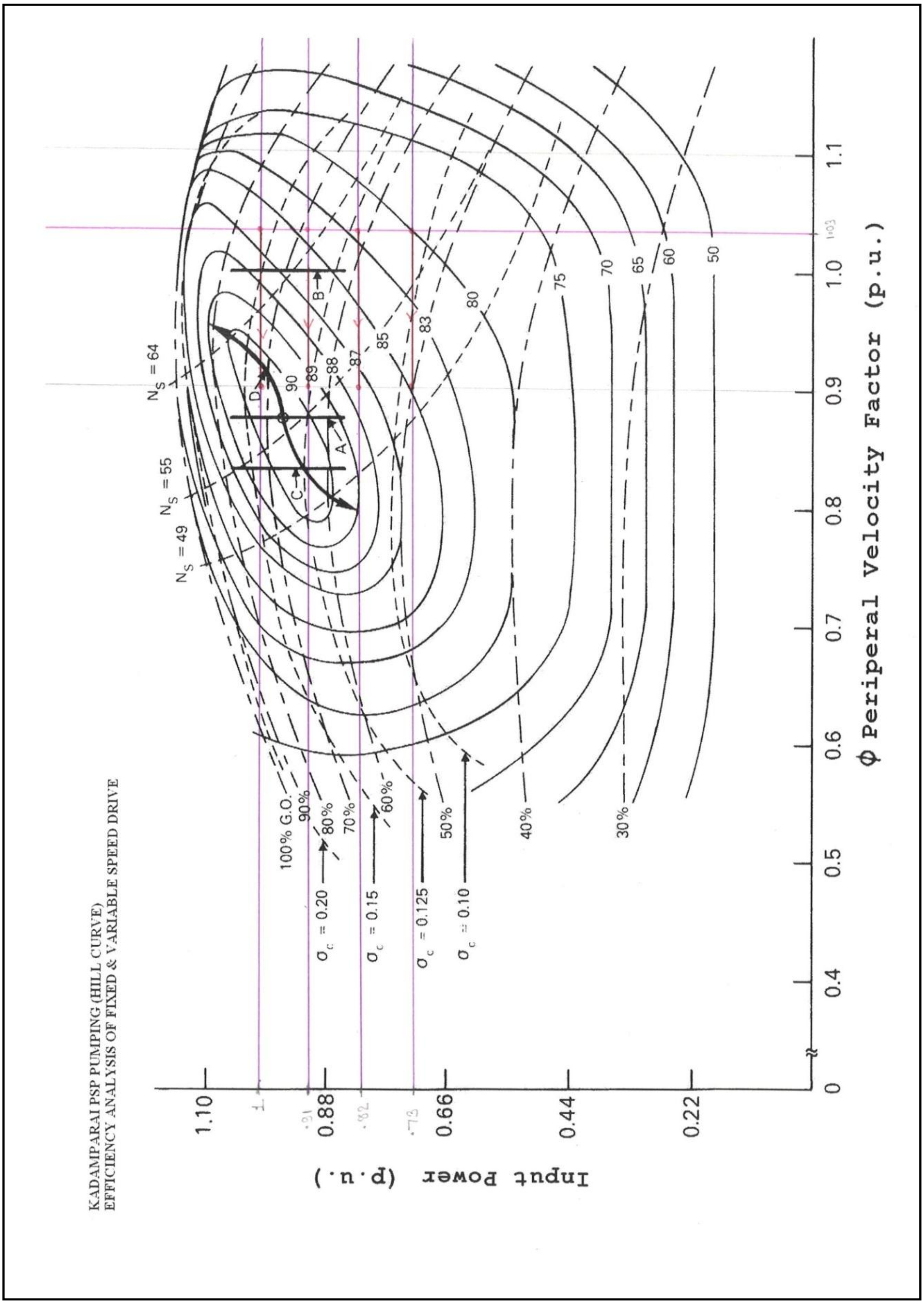
Annexure – 11 (contd.)

Hill curve (Pumping)



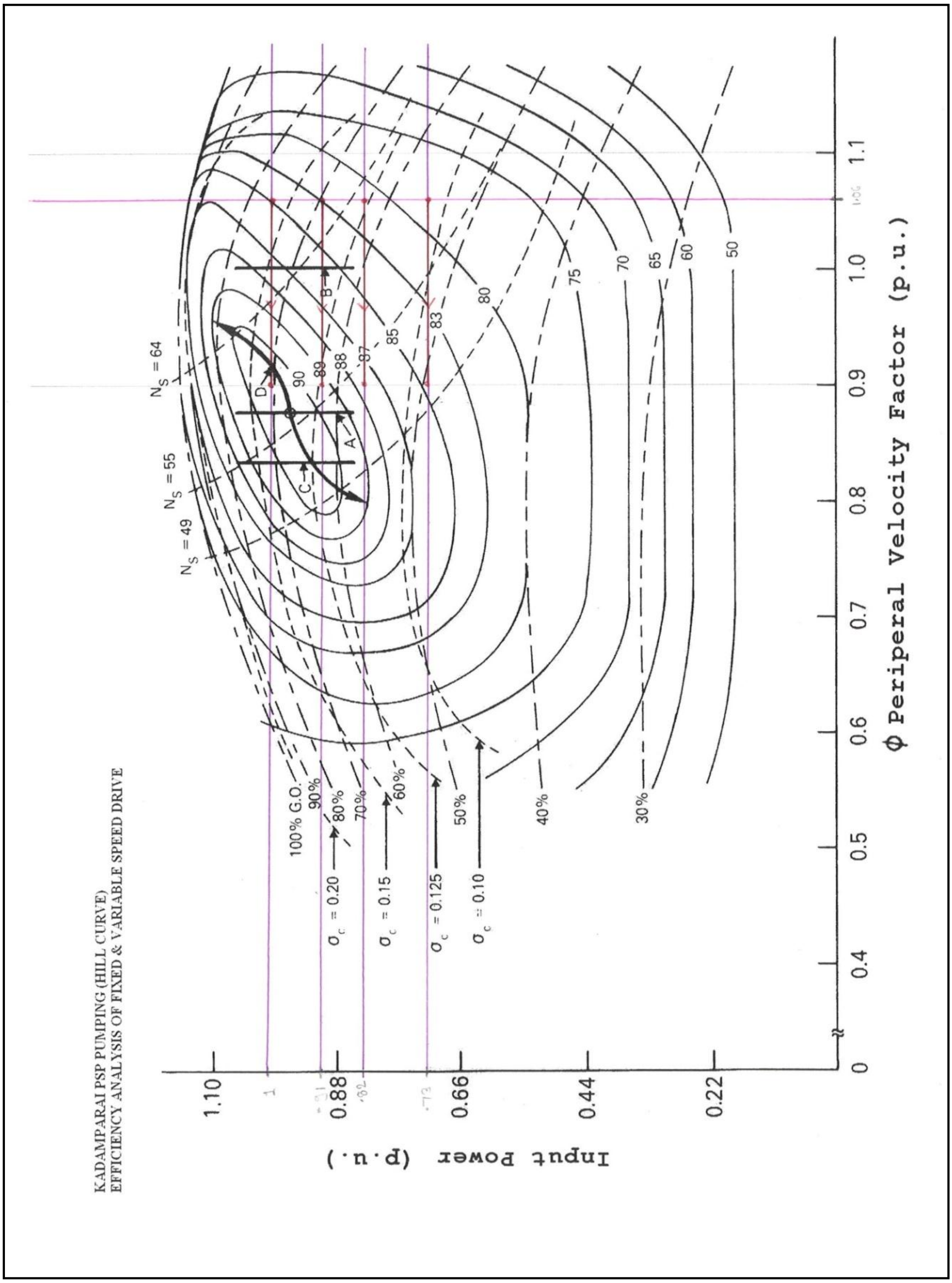
Annexure – 11 (contd.)

Hill curve (Pumping)



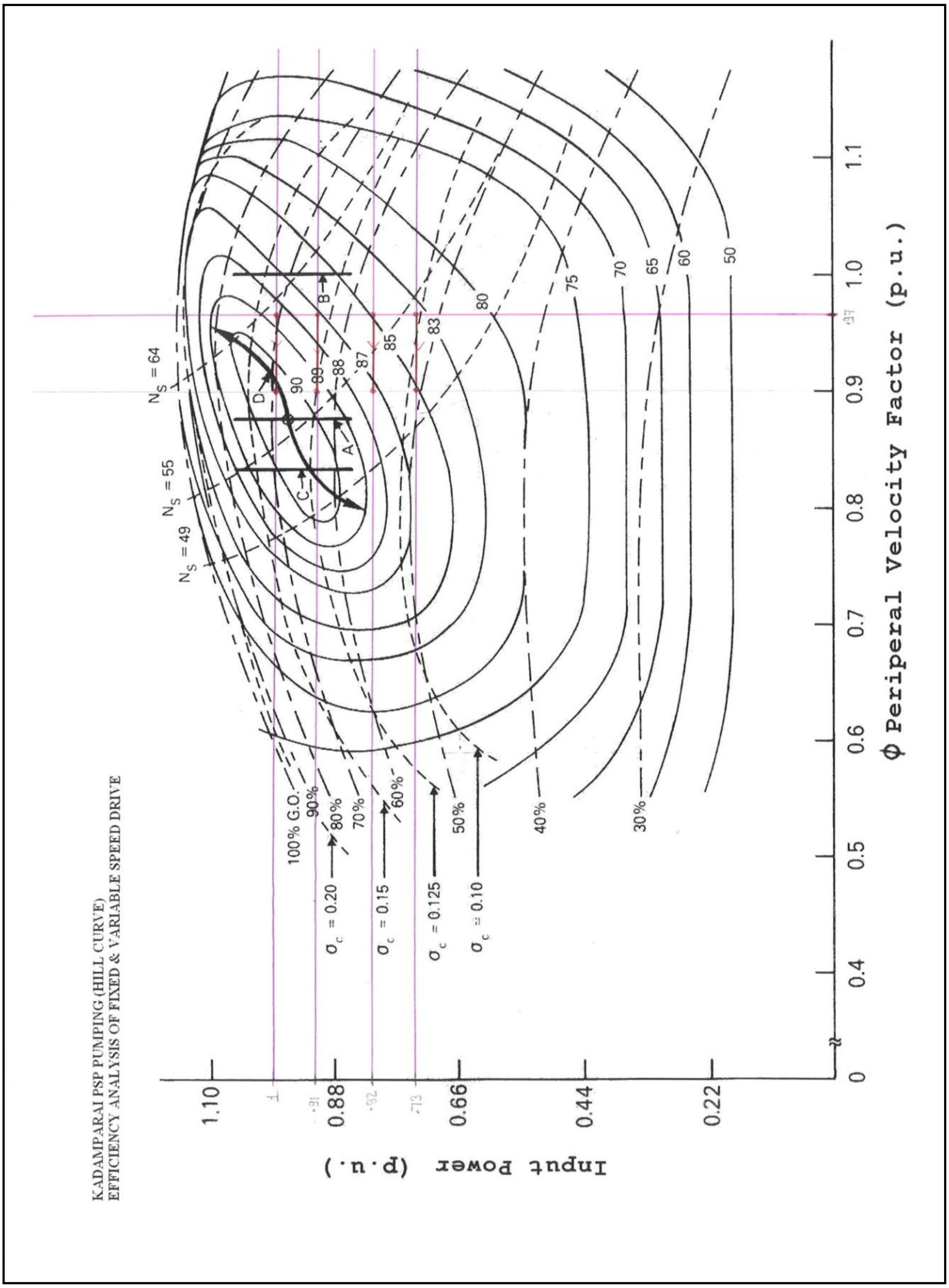
Annexure – 11 (contd.)

Hill curve (Pumping)



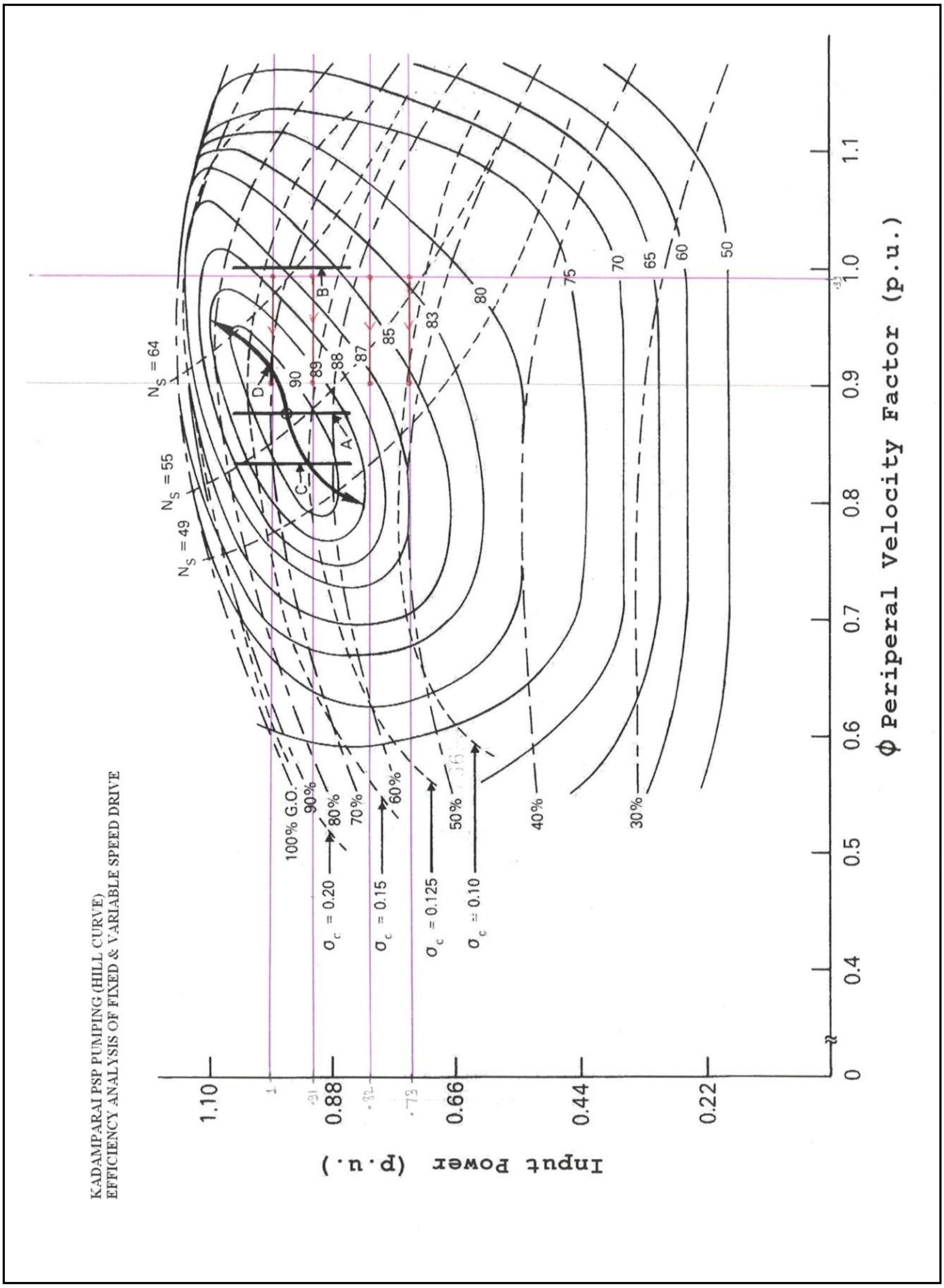
Annexure – 11 (contd.)

Hill curve (Pumping)



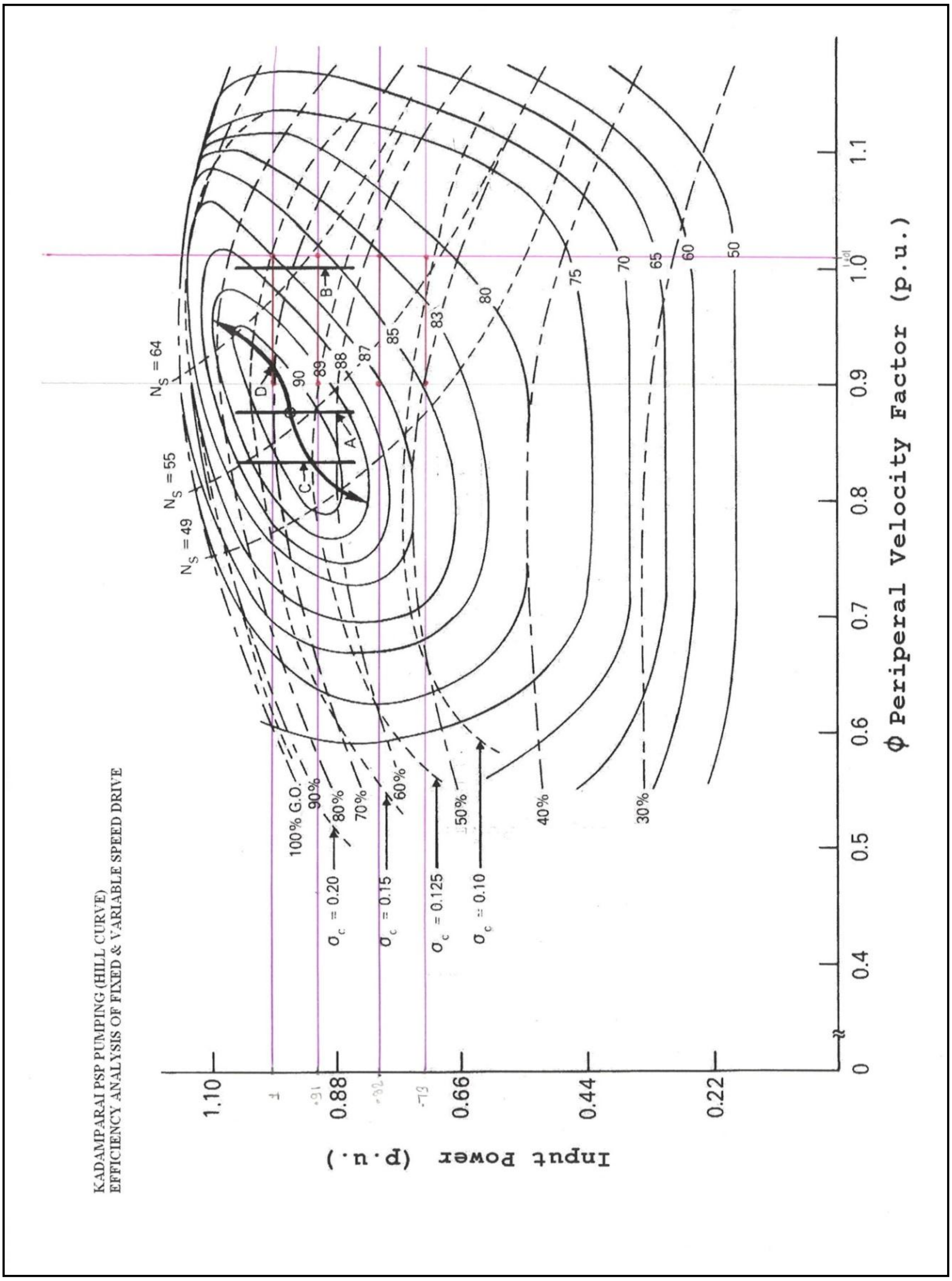
Annexure – 11 (contd.)

Hill curve (Pumping)



Annexure – 11 (contd.)

Hill curve (Pumping)



Annexure – 12

Actual Purchase and Energy Sales of TNEB

Year	Sale of energy (MU)	Purchased Energy (MU)	Purchase cost paid (Crores)	KPH Pump consumption (MU)	Auxiliary energy consumption (MU)	Line loss (MU)	Gross energy (MU)
2002-03	36347	21263	5703.14	185	1878	7979	46389
2003-04	38697	25384	6663.82	468	1838	8495	49498
2004-05	41200	25895	7083.02	232	1869	9044	52345
2005-06	44592	29811	8040.88	555	1791	9788	56726
2006-07	50159	34082	9964.96	417	1976	11011	63563
2007-08	53370	37574	12493.80	390	1914	11715	67389

Source: TNEB Statistics at a Glance 2007- 08

Annexure – 13[23]

Table 142: Fixed Charges for Kadamparai Generation Circle

	Petition (%)			Revised Submission (%)			TNERC Approval (%)		
FY	2010-11	2011-12	2012-13	2010-11	2011-12	2012-13	2010-11	2011-12	2012-13
Depreciation	5.07	5.33	5.78	3.96	4.00	4.36	3.96	3.96	4.36
Interest on Loan	1.78	8.53	13.60	1.20	1.29	1.38	1.20	1.29	1.38
Return on Equity	2.89	3.60	5.42	3.02	3.56	5.47	2.49	3.29	4.49
O&M Expenses	8.58	9.16	9.51	8.58	9.16	9.51	8.58	8.89	9.24
Other Debts	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Less: Misc Income	0.09	0.13	0.13	0.09	0.13	0.13	0.09	0.13	0.13
Total	**18.22**	**26.53**	**34.22**	**16.71**	**17.91**	**20.62**	**16.18**	**17.33**	**19.42**

Annexure – 14

Cost of energy at various points - Average rate of realization (Paise/kWh)

2002 - 03	2003 - 04	2004 - 05	2005 – 06
255.61	283.95	297.28	307.63

Source: TNEB Statistics at a Glance 2007- 08

Annexure - 15

Generation and sale cost of KPSP (Paise/kWh)

2009-10		2008-09		2007-08		2006-07	
Generation cost	Sale cost	Generation cost	Sale cost	Generation cost	Sale cost	Generation cost	Sale cost
81.82	311.08	132.71	311.19	95.60	317.03	90.75	310.16

Source: CEA

Annexure – 16

Details of tariff approved for power purchasing from central generating stations

Name of the power plant	Annual capacity charges in (Crores)	Provisional energy charges in (Paise)	Year
NLC TPS - 1	152.99	132.11	2008-09
NLC TPS - 2 Stage - 1	121.96	121.00	2008-09
NLC TPS Stage - 2	175.19	121	2008-09
NLC TPS - 1 EXP	256.61	114.01	2008-09
NTPC Ramagundam Stage – 1 & 2	479.71	82.84	2008-09
NTPC Ramagundam Stage - 3	263.31	86.62	2008-09
NTPC Talcher Stage - 2	863.5	58.73	2008-09
MAPP	Single part	181.18	2006-11
KAIGA Atomic	Single part	279.50	2005-10
Average		**131.99**	

Source: TNEB Statistics at a Glance 2007- 08

Annexure – 17

Calculation of annual net benefit for KPSP

Finance year	Generation (by natural inflow) (MU)	Generation (by pumping) (MU)	Total generation (MU)	Auxiliary energy consumption (MU)	Generation at Station Bus (MU)	Pumping energy consumption (from Thermal) (MU)	Pumping energy consumption (from Wind) (MU)	Cost of pumping energy consumption (Thermal) (Rs. x 10^7)	Cost of pumping energy consumption (Wind) (Rs. x 10^7)	Energy generation Cost (Rs. x 10^7)	Annual fixed cost (Rs. x 10^7)	Total Expenditure (Rs. x 10^7)	Revenue (Million rupees)
2002-03	95	108	203	1.40	201.60	144	29	18.86	7.83	51.61	45	71.69	-202.54
2003-04	57	351	408	2.90	405.10	444	24	58.16	6.48	115.05	45	109.64	54.04
2004-05	82	174	256	1.79	254.21	207	25	27.12	6.75	75.50	45	78.87	-33.67
2005-06	165	416	581	4.06	576.94	517	38	67.73	10.26	177.70	45	122.99	547.11
2006-07	126	312	438	3.00	435.00	374	42	48.99	11.34	134.85	45	105.33	295.16
2007-08	155	302	457	3.20	453.80	378	25	49.52	6.75	143.85	45	101.27	425.87
2008-09	116	178	294	2.00	292.00	219	18	28.69	4.86	90.81	45	78.55	122.63
2009-10	55	364	419	2.93	416.07	435	50	56.99	13.50	129.40	45	115.49	139.13
2010-11	113	459	572	4.00	568.00	549	62	71.92	16.74	177.22	45	133.66	435.57
2011-12	106	400	506	3.54	502.46	478	55	62.62	14.85	156.77	45	122.47	343.00

LIST OF PUBLICATIONS

International Journals

1. **Sivakumar N**, Devadutta Das, Padhy NP, Senthilkumar AR, Nibedita Bisoyi, **"Status of pumped hydro-storage schemes and its future in India"**, Renewable and Sustainable Energy Reviews, Vol. 19, pp. 208-213, March 2013. **(Impact Factor: 5. 627)**
2. **Sivakumar N**, Devadutta Das, Padhy NP, **"Variable speed operation of reversible pump-turbines at Kadamparai pumped storage plant – A case study"**, Energy Conversion and Management, Vol. 78, pp. 96-104, February 2014. **(Impact Factor: 2.775)**
3. **Sivakumar N**, Devadutta Das, Padhy NP, **"Economic analysis of Indian pumped storage schemes",** Energy Conversion and Management. (Under review)
4. **Sivakumar N**, Devadutta Das, Padhy NP, Senthilkumar AR, Nibedita Bisoyi, **"Deriving operating rules for mixed pumped storage plant: Kadamparai - A case study",** Water Resources Planning and Management. (Under review)

International Conference

1. Devadutta Das, **N. Sivakumar,** N. P. Padhy, **"Renovation & modernization of Kadamparai pumped storage plant by using variable speed turbine-generator"** 18th International Seminar on Hydropower Plants, November 26 – 28, 2014,Vienna, Austria. (Accepted)

National Conference

1. **N. Sivakumar**, Devadutta Das, N. P. Padhy, **"Pumped storage schemes – A bibliographical survey"** Paper ID – 116, National Conference "Electrical Machines and Power Systems (**EMPS – 2011)"** organized by Electrical and Electronics Engineering Department of Pondicherry Engineering College, Puducherry on 11th February 2011.