CONTROL AREA WISE OPTIMISATION OF POWER PURCHASE AND HYDRO SCHEDULING: A PRAGMATIC APPROACH

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CERTIFICATE

This is to certify that the thesis "**CONTROL AREA WISE OPTIMISATION OF POWER PURCHASE AND HYDRO SCHEDULING: A PRAGMATIC APPROACH**" submitted by **Anand S. R.** to the Cochin University of Science and Technology, Kochi for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by him under our supervision and guidance at the Division of Electrical Engineering, School of Engineering, Cochin University of Science and Technology. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma. All the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral committee have been incorporated in this thesis.

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DECLARATION

I hereby declare that the work presented in the thesis entitled "**CONTROL AREA WISE OPTIMISATION OF POWER PURCHASE AND HYDRO SCHEDULING: A PRAGMATIC APPROACH"** is based on the original research work carried out by me under the supervision and guidance of **Dr. Jagathyraj V. P,** Professor**,** School of Management Studies, Cochin University of Science and Technology, Cochin-682 022 and under the co-guidance of **Dr. C. A. Babu**, Professor and Head, School of Engineering, Cochin University of Science and Technology, Cochin-682 022 for the award of degree of Doctor of Philosophy with Cochin University of Science and Technology. I further declare that the contents of this thesis in full or in parts have not been submitted to any other University or Institute for the award any degree or diploma.

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ABSTRACT

Electricity is the most preferred form of energy from the perspective of the user mainly on account of the ease of controllability, availability, high efficiency of conversion to other forms of energy and cleanliness. Availability of electricity on round-the-clock basis and its price at the consumer's end have social and political significance. The change of Electricity Industry from the "natural monopolistic" stature, emerged with the concept of "economy of sizes" in the medieval period, to the present "market-based approach" has called upon the need to optimise the operation of the grid. The optimisation issues have become more prominent with the increasing penetration of renewable power and the freedom of the consumers to procure power from any source. In India, the need for optimisation of power system operation is imposed on the utilities by the government policies. The cost of power delivered is determined and managed control area wise, the control area generally being aligned to the geographical boundaries of the states.

The problem selected was the development of a simple, robust and transparent method for optimisation of the cost of power delivered in a control area. About 200 documents were reviewed as part of the work. In practise, the management needs to view and modify intermediary steps in the optimisation process. Review of the literature revealed that holistic approach to optimise the cost of energy delivered in a control area is not attempted fully. The methods found in the research world are mostly too advanced for the practising managers and often requires complete modification of the method/ software to accommodate changes in the strategy and policies of the government from time to time.

The burgeoning gap between demand and availability of electricity in Kerala due to the restrictions in setting up of large power plants within the state with reasonable

cost of generation necessitated decision on optimum purchase of power from various generators on competitive basis and optimisation of hydro generation within the control area irrespective of ownership and local optimum of the generator concerned. This thesis emerged on the basis of the works carried out for this purpose during the period from 2007 and implemented successfully since then. The methods developed applied on Kerala power system progressively resulted in significant improvement on cost of power procurement.

Specifically, the objectives of this research work are:

(i) To study the present optimisation methods followed in the electricity sector for power procurement and to develop a method to analyse the strengths, weakness, opportunities and challenges of an electricity distribution licensee with respect to the power supply management

(ii) To develop a simple, robust, practical means for estimating the power procurement strategy for a control area

(iii) To develop a simple, robust and practical method for optimisation of storage in the reservoirs from the optimisation perspective of minimisation of cost of power delivered in the control area

(iv) To suggest further optimisation for ensuring availability and minimising the cost of power delivered

About 200 optimisation studies were reviewed as part of the work, of which 113 are classified and specific references have been made. Being a work with practical application in view, the relevant regulations and rules as existing in India have also been made part of literature review. Most of the methods used in similar works suffered from following major drawbacks:

- The approaches are generally confined, for example, to a particular generation system, hydro thermal coordination optimisation, market operation etc. which are done in a short time span, thus having the issue of local optimisation

- Most of the hydro generation optimisation approaches were confined to a particular generation scheme in a power system where the daily generation limit is either fixed or assumed. The determination of the daily generation limit from hydro could not be seen attempted except in hydraulically coupled generation facilities.

- Load forecast over longer periods for taking a decision in investment and contracts is attempted in several ways, but quite often with large variances resulting in surplus and deficit of power during different periods.

- The concept of control area for power management is not seen considered in the optimisation studies, which is critical for ensuring the energy security at appropriate price in the area.

The ultimate objective of the work being to ensure adequate availability of electricity at the lowest possible rate with reasonable risk mitigation within a control area, the optimisation is on the cost of energy delivered within the control area and is achieved by a combination of optimisation of the power purchases and optimisation of internal hydro generation. The solution is approached mainly in four different steps.

- SWOC analysis of control area with the perspective of optimisation on cost of energy delivered

- Simple and robust method to assess the load profile and to determine the base load and peak load requirements with specific reference to power purchase / sale on a longer horizon in commensuration with the factors affecting the price of power in the long-term and short-term markets

- Simplification of the unit commitment of hydro units by linking it directly to the merit order dispatch by determination of a "merit order price" for hydropower as against the rules of thumb and other assumptions. The determination of "merit order price" is on deterministic principles derived from statistical inferences.

- Assessment of spill threat of reservoirs and to apply the results in the optimisation of storage in the reservoirs.

The practical impact of the methods developed in the reduction in the cost of power delivered in the control area was verified with the Kerala power system from the year 2009-10. The power purchase as per long term contracts and prudent hydro generation management in the case study of Kerala Power system reduced the high cost energy absorption at the level of 16.23% of the consumption in 2009-10 to 0% by 2017-18. The cost of power purchase from sources other than hydro and central sector power stations for Kerala reduced from ₹ 8.95 to ₹ 4.12 per kWh during this period, a reduction of about 55%. The storage in the reservoirs also improved significantly to the end of monsoon period, reducing the dependency of hydro management in summer with annual inflow.

The methods developed are based on simple tools and can be implemented using MS Excel. The data required for the analysis is also readily available with any utility. The intermediary steps are also visible and can be modified with minimum effort and is not sophisticated. The methods are therefore universal in general, which requires only customisation with respect to the modelling of the system.

Key Words

Power System, Electricity Market Operation, Hydro Storage Optimization, Power Purchase Optimization, SWOC Analysis, Long Term Load Forecast

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GLOSSARY

The following are the some of the commonly used terms in this thesis

Grid	Electrical Grid is an interconnected network for delivering electricity to the consumers and to inject power by the generators. Grid consists of transmission lines, transformers and reactive power compensators
Control area	An electrical system bounded by interconnections (tie lines), metering and telemetry which controls its generation and / or load to maintain its interchange schedule with other control areas whenever required to do so and contributes to frequency regulation of the synchronously operating system
Consumer profile	in this thesis, the word “consumer profile” describes the grouping of consumers based on the common traits and behavioural pattern of consumption of electricity
Counter flow	Counterflow is a term used to explain the difference between the contracted power flow in a transmission corridor and the actual power flow. The counterflow is considered in the determination of transmission capability of a transmission system and in the determination of transmission constraints.
Distribution utility	In Electricity industry, the term utility is used to denote a major provider of electricity, often a public company. In Indian context, it refers to major distribution licensees who distribute power to retail consumers, usually the successor entities of the previous electricity boards.
Load Curve	In a power system, load curve (also referred to as load profile) is a chart illustrating the variation of demand (electrical load) over a specific time. The time can be daily, weekly, monthly or yearly. Load curve indicates the actual consumption of electricity at any point of time
Load duration curve	In Load Duration Curve, the load is arranged in descending order before plotting. It is used to indicate the duration sustained at each load level. In other words, it depicts the capacity utilisation clearly.
Load factor	Load factor is the ratio of average load to the peak load for the same duration.
Load Profile	Same as load curve

Marginal cost	Marginal cost in this thesis means the change in the opportunity cost that arises when the quantity produced in incremented by one unit or in other words, the additional cost required to produce the next unit.
Scheduling	Scheduling (of power) means the process of estimating the load (demand for electricity) and to order the dispatch of the required quantity of power at the required time.

ABBREVIATIONS

PoC	Point of Connection (mechanism for apportioning transmission charges and transmission losses in interconnected grid)
SLDC	State Load Dispatch Centre
RLDC	Regional Load Dispatch Centre
NLDC	National Load Dispatch Centre
CEA	Central Electricity Authority (India)
CERC	Central Electricity Regulatory Commission (India)
CTU	Central Transmission Utility
SERC	State Electricity Regulatory Commission – reference to Kerala SERC in this thesis
SWOC (Analysis)	Strength, Weakness, Opportunity, Challenges (Analysis)
(Solar) PV	Solar Photo Voltaic (systems)
MCM	Million Cubic Meter
MU	Million Units (10^6 kWh)
ISO	Independent System Operator
TSO	Transmission System Operator
PPA	Power Purchase Agreement

OPERATIONAL DEFINITIONS

- Availability Based Tariff – A tariff structure evolved in India to settle the payments between generators and utilities and between utilities for bulk power purchase/ sale
- Utility in the electricity sector in India is an entity engaged in statutory obligation of transmission or distribution of electricity to consumers within its area of control.
- Power Contracts – In this thesis, all power procurement for distribution to the consumers is treated as a contract by the distribution licensee with the generators. The own generation of the distribution licensee, i.e., from the generating stations owned and operated by the same distribution company, are also treated on the same platform as the decision to buy or make is also residing with the company.
- Base Power Contracts refer to the contracts to supply power uniformly on round-the-clock (RTC) basis. In the case of own generation, this refers to the technical minimum generation of the internal power plants.
- Peak power Contracts refer to the power purchase contracts for supplying peak power whenever the system demands. With reference to the internal generators, this refers to schedulable power.

NOTATIONS

E	=	Energy met for the day in MWh
E_{Base}	=	Base Demand in MWh
E_{MP}	=	Marginal Energy component constituting the peak in MWh
P_p	=	Average demand during Peak hours in MW
P_o	=	Average demand during other than Peak hours in MW
h	=	Duration of Peak demand in hours
LF	=	Load factor
$E_{H\text{-}D}$	=	Daily generation possible from Hydro sources in MWh
$P_{H\text{-}Base}$	=	Base hydro generation in MW
$P_{H\text{-}Max}$	=	Maximum Generation possible from all hydro stations during peak in MW
$E_{H\text{-}Base}$	=	Daily base generation possible from Hydro sources in MWh
Γ_0	=	Present storage
Γ_{-1}	=	Storage at the beginning of the control period,can be one day, month or year as the case of analysis
I_{-1}	=	Inflow during the control period
ϑ_{-1}	=	Depletion of water during the control period
ζ_{-1}	=	Spill during the control period
δ_{-1}	=	Evaporation and other losses of water from the reservoir during the control period

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Energy is one of the basic necessities for sustaining life. Better utilization of energy in controllable manner has improved the convenience of peoples, led to rapid development of industrialisation and increase in per capita income and thus overall economy of the countries. Availability of energy at reasonable price is therefore a basic need for economic development of any country. It is often concluded that the per capita consumption of energy of a country is an indicator for the standard of living of the people in the country, though some correction factors are to be applied with respect to tropical countries and temperate zone countries.

The requirement of energy is manifested as heat, light, motive power etc. From the history of mankind, it can be seen that the civilisations emerged where availability of energy sources suitable for taming was abundant. Transportation of energy from one location to another had been the biggest challenge. Electricity as a convenient form of energy, capable of economic and easy transportability, was put into commercial use by 1870s with the use of arc lamps for light house illumination and street lighting [1]. Penetration of electricity into industrial sector increased from 1884 with the development of motors by Frank Sprague. Development of ac transmission and transformers by 1886 enhanced the utilization of electricity in faraway places from the point of generation. The development of poly-phase systems by Nikola Tesla made ac systems more attractive. Electricity as a form of energy has been accepted superior to other forms of energy mainly on account of the following reasons.

(i) Convenience – Electricity is the most convenient form of energy. It can be converted to other forms of energy very easily and efficiently.

(ii) Controllability- Electricity is the most controllable form of energy. At the flip of a switch (breaker), any amount of energy can be availed with ease.

(iii) Economy and Flexibility – Electricity is the cleanest form energy at the point of utilization. Transportation of energy in the form of electricity is the cheapest among all forms of energy. This makes it possible to produce energy from any source at a place where it can be done most economically. Pit head coal based stations of large capacity has made it possible to extract energy in the most economical way, compared to transportation of coal itself to the place of utilization.

There are some disadvantages also for electricity as a form of energy. The most important among them is the difficulty in economic storage now. The storage of electricity at user's premises is quite expensive and yet to be economical in sizes. Electricity system is maintained in grid concept in general, where all generators inject to the grid and all users draw power from the grid, whereby the quality of electricity is decided by the collective contribution of all generators and users and no particular generator or user can claim to have a different quality of supply other than that decided by the grid parameters. Degradation of quality, intentional or unintentional, can pollute the electrical grid and the effect is shared by all connected entities unless precautions are taken. The concept of grid had evolved in response to stability of supply and the optimisation on the cost of energy supplied, contributed by different means.

Optimization of the Power System Operation aims at delivery of quality power and lowest possible cost. The major qualitative factors reckoned in the industry are frequency, voltage and reliability. In the electricity grid, it is not possible to take a quality corrective action by a single utility alone especially with respect to system frequency and reliability. Variation of frequency is a feature associated with the power systems of developing countries alone, where the demand – supply gap is also considerable. The influx of renewable power such as solar and wind, with its uncertainty, along with the deficit condition in load-generation balance, further worsens the situation. The implementation of Availability Based Tariff in India (ABT) in 2003 is regarded as a landmark in regulatory measures to enforce grid discipline through commercial signals instead of the command and control culture [7], [8]. Voltage control is more of a local issue, though some global issues across the grid also affect it partially. Voltage control affects the quality of power delivered in the vicinity but can also affect the cost of the power delivered if the nodal voltage goes to a level of affecting the transmission capability. Reliability of supply at the consumer end is of high importance. In the case of loads such as continuous process industries, the effect of reliability can be directly transferred to commercial figures by computing the production loss, whereas in some other cases, the complete monetary impact may not be easily tangible. The cost of power delivered to the consumer is the major factor considered in the optimization of power system operation, as significant as technical parameters.

Electricity is the most preferred energy source at the point of consumption. Minimisation of cost of electricity at the point of consumption is therefore as important as the reliability of supply.

1.2 PRESENT SCENARIO

The electricity consumption is expected to continue to increase in developing countries like India on account of the improvement of living standard of the people and the increase in the industrialisation. In developed nations the electricity consumption is remaining almost static for past several years. The estimated demand for electricity in India by 2050 is four to five times the present requirement [2]. Positive slope in the GDP profile, as expected for India now, indicates increasing industrialization and urbanization. Industrialization directly causes increase in the consumption of electricity for manufacturing and service sector. Availability of electricity at affordable rate is often one of the factors deciding the location of an industry. In industry parlance, the electricity industry is regarded as "mother of all industries".

It is accepted that increase in per capita consumption of energy indicate better standard of living. The term energy is often synonymously used for electricity nowadays. Penetration of television, computer, air-conditioning, house hold activities conventionally done by petroleum products like kerosene and gas getting replaced by electricity, activities mechanically done by hand like cloth washing, dish washing etc. getting replaced by electrically operated equipments etc. contribute to this. Growth of hospitality sector and entertainment sector are other core areas contributing to electricity consumption. The concept of shopping malls and entertainment hubs has contributed to significant increase in commercial utilization of energy, which is fuelled by the purchasing capacity of individuals in commensuration with the increase in GDP. Electricity is the most convenient form of energy at the disposal of every individual.

It is estimated that by 2030, electricity generation will account for nearly half of world consumption of natural gas. The electricity sector will absorb most of the future energy investment. Power generation, transmission and distribution will absorb almost 60% of total energy investment. If investment in the fuel chain to meet the fuel needs of power stations is also included, electricity's share rises to more than 70%. As per the studies of International Energy Agency (IEA) in their annual report, more than half of the investment in the electricity industry will go to transmission and distribution networks [3].

Affordability of electrical energy is identified as one of the key factors influencing economic growth and is addressed at policymaking level appropriately [4]. Now, the rules and regulations permit any person to generate, transmit, or consume electricity in any part of the country or even outside. This has changed the dimensions of system operation activities where the commercial matters assume significance among the managers of the sector who were earlier worried only about technical issues alone of load – generation balancing. The policy changes have started paying its dividend in various aspects. Optimization of operation of the grid with the strong regulatory structure at the apex made sea of changes in the industry. Electricity is now regarded and managed as a commodity, much like any other commodity, but with the inherent technical limitations. [5]

Tracing the history of electricity supply business, it can be seen that the competition was brutal and inefficient in the beginning. For instance, it is observed that there were twenty-four power companies in Chicago alone during 1887 – 93 period, with overlapping distribution lines. But, the cost of power delivered was also very high. The concept of natural monopoly for the sector emerged for reducing the cost of energy supplied, which finally led to regulatory laws and establishment of state utility commissions [6]. Integrated utilities remained natural monopolies. As the transmission system made long distance transfer of electrical energy possible, regulated vertically integrated utilities became well established. But, the vertical integration proved to be inefficient, as the power system developed. By 1990s, market-based structure was in consideration and was introduced with deregulation and disintegration of the industry. It is also evident that developments in the transmission technology, rather than the changes in the generation technology, led to the vertically integrated natural monopoly in the beginning and further development of the transmission technology led to the removal of natural monopoly character of the electricity sector. The situation led to emergence of system operation as a separate function with two major models across the world: Independent System Operator – ISO and Transmission System Operator – TSO. Indian context is not fitting to either of these models fully and is distinct. In this thesis, stress has been put on the operational efficiency rather than the working models of system operation. The Indian scenario is taken in this thesis.

Recently, the environmental concern has been one of the key factors in many developmental activities, which has contributed to selective utilization of resources for producing electricity. The utilization of renewable sources with high degree of variability and low predictability has put tremendous pressure on the system operator and necessitate additional balancing mechanisms. As a result, the optimization in real time operation of the grid has become complex.

1.3 CONTROL AREA

The concept of control area is important for any optimisation. The control area demarcates the responsibility and scope of the activities. In India, Electricity is a matter in the concurrent list of the written constitution, which means that the state government as well as the union government are stakeholders. Electricity being a very sensitive matter for the governments in view of the social and developmental influences, the state government has a consolidated view on several aspects involving maintaining availability, offering subsidies to target groups etc. The investment made in the sector by the Union government through public sector companies like NTPC (National Thermal Power Corporation), NHPC (National Hydro Power Corporation), NLC (Neyveli Lignite Corporation) etc. is allocated to the various states on regional basis. The state government investments are intended to the welfare of the people of the state and confined to the geographical limits of the state. The Electricity Act 2003 [5] with subsequent amendments and the policies formulated on that stratum provides for the dissociation of the erstwhile vertically integrated organization called SEB (State Electricity Board) into different companies on the basis of functional units. Distribution companies are the licensed agencies to deliver electricity to most of the end users by procuring power from suitable agencies (by selection or by force) and by arranging transmission network. In this scenario, ideally, the control area has to be delimited to the area of service of each distribution company. Control area in the context of Indian power system is defined in Indian Electricity Grid Code (IEGC) as “an electrical system bounded by interconnections (tie lines), metering and telemetry which controls its generation and/or load to maintain its interchange schedule with other control areas whenever required to do so and contributes to frequency regulation of the synchronously operating system” [9].

In this concept of control area, every independent generating company, transmission network, the area of distribution licensee and even a major consumer remaining independent (not a consumer of area distribution licensee) etc. qualify for separate control area. However, in the hierarchical system operation structure, comprising of National Load Dispatch Centre (NLDC), Regional Load Dispatch Centre (RLDC) and State Load Dispatch Centre (SLDC), the control area concept matches with the area coming under each of these control centres.

The boundaries of the state have been taken as the boundary of the control area for administrative purposes and coordination of the development activities. Naturally, it follows that any optimisation on cost of power delivered also should align to the geographical boundaries of the state. Several states, where multiple distribution companies exist, have formed common power procurement cells. The coordination of generation from state owned generating stations also come under the ambit of such cells. As the state investments are also high in the sector, the control area is ideally to match with the geographical boundaries of the state. Indian Electricity Grid Code as well as the government policies, rules and regulations assume the spread of the control area matching with the geographical limits of the state. Considering all these factors, for all practical purposes, the control area can be delimited to the geographical boundaries of the respective state in most cases.

The concept of control area in this sense, when generalised, means a bounded power system managing its own generation, import of power, market operation and transmission system operation for managing the power supply within that area through different transmission licensees, distribution licensees and bulk consumers.

1.4 COMPETITION IN THE POWER SECTOR

The electricity sector developed from islanded environment to vertically integrated business model to take advantage of the economy of sizes. Though this was achieved, the interference of the political leadership often outweighed the commercial decision making of such vertically integrated utilities and most of the electricity companies went into red almost in all countries. This can be viewed as dumping all inefficiencies of several other sectors such as public services sector, sick industries, agriculture etc. on the electricity sector, which was not compensated through the budgetary support from the government whereas the entities in the electricity sector had to follow the decisions of the government. Over the period of time, the vertically integrated entities failed to perform, could not deliver electricity to all applicants and failed to meet the expectations of the existing consumer. All these led to the concept of inducing competition in the field without disturbing the concept of grid. All countries have followed similar logic with slight difference in implementation and the electricity sector moved into a market-oriented structure with licensees for distribution and transmission of electricity. Decentralisation and deregulation emerged as the most suitable reform in power sector. With these reforms the interference of the government in tariff fixation and operational matters also got eliminated to a large extent.

In India, the promulgation of Electricity Act 2003 and the subsequent regulations by the central and state electricity regulators on open access and trading of electricity enabled the market operations, creating competitive environment. (There were some attempts before that to liberate the industry, but not comprehensive). Now, the competition is effective among the generators to supply power and among the consumers and the licensees to grab the cheapest power available to them. The licensees in India are also obliged to meet the demand of the consumers in their area of jurisdiction and hence the consumers going directly to the market are the favoured entity in Indian context. The universal supply obligation in the Electricity Act 2003 has been the result of several incidents of selective behaviour of the suppliers in the country and abroad in the past.

The consumers are permitted to purchase power from the market while retaining their status as a consumer of the local distribution licensee. The price discovery in the market depends on a number of factors, typically optimisation of heat rate[1] by the generators, start-stop cost of generators, comfort level attained in recovering fixed charges etc. The price discovered in the market could, therefore, be lower than the actual cost of generation on average basis (energy charges as per the regulatory terms) in some occasions. Naturally, the affluent consumers who can go to the market directly, retaining the status of consumer of the local distribution company, can make use of the market rate variations advantageously resting in significant reduction in the electricity charges. On account of the universal supply obligation [5], the distribution licensees are mandated to maintain enough power purchase contracts to meet the demand of power of such consumers when they do not go to market. The associated fixed charges (capacity charges) would reflect in the cost of procurement of power and gets socialised to all consumers unless proper corrective steps are taken in the tariff design. Several measures such as cross subsidy have been provided in the policy to alleviate the tariff shock all on a sudden. On the contrary, such cross subsidy is potent enough to the level of affecting the competitiveness of Indian industries on global market [10] in long run.

By virtue of the inheritance of the vertically integrated business structure, most of the distribution-licensees in India have sizeable own generation capability, which also opens up several possibilities for optimization of their portfolio management. Separation of the business units of generation and supply, this optimisation is however lost. The optimization strategy has to be global rather than local, for

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[1] Heat rate in respect of generating station is the heat energy required for producing on unit of electricity, expressed in kCal/kWh. Heat rate is dependent on the real time loading of the generator in general, increases as the loading comes down.

obtaining the desired results of inducing competition on a larger canvas. This work is precisely intended to develop the strategies which can be implemented practically to achieve this goal from the perspective of state wide power procurement cost optimisation.

1.5 EXISTING METHODS AND LIMITATIONS

In the existing methods of grid operation optimisation, the concept of market operations was not exploited effectively. The basic approach adopted in almost all states in India was found to be similar. Power procurement and own generation were considered separately, though the merit order scheduling was done. This approach had subjectivity in several scheduling decisions, resulting in sub-optimal solutions. The concept of power procurement was limited to the purchases from the market or from short-term markets. All internal generation was kept separate and had merit order among them. These are evident in the tariff orders of the regulatory commissions. [13]

The long-term approach was to establish generating stations locally under the vertically integrated structure. The share allocation from the generating companies owned by the Union Government to make use of "the economy of sizes" was also considered at par with the internal generating stations for meeting the balance between demand and availability. Being a predominantly government business, there were no cut throat competition or much research into economy of operation. The hydro scheduling was done as per thumb rule and power cuts and load shedding were not viewed seriously. The system also did not have any proper mechanism for a performance evaluation.

In the case study taken for this work, the hydro generation management in Kerala was done with thumb rules such as minimisation of generation from the hydro stations with storage type reservoirs during monsoon period and maximisation of generation from the stations with small reservoirs. Naphtha based generation and diesel based generation, costlier options, also found place in the portfolio. The generation pattern from each station during each month was based on thumb rules. The concept of rule curves with minimum statistical trends resulted in sub-optimal scheduling of generation and power purchase.

1.6 MOTIVATION

Minimisation of the cost of electricity delivered to the consumers in a control area is more important than the profit maximisation of individual stake holders. The policy of separating the business units of transmission, generation and distribution for inducing competition in the industry also intends the minimisation of the cost of power supplied in the control area. Competition among the similar verticals of industry, with the aim to maximise the profit of each vertical, need not achieve this target of minimising the cost of energy served in the control area. Majority of the research papers attempt the power system optimisation studies with limited scope of maximisation of profits, maximisation of social benefit etc. Though several approaches have been made in this regard, a simple, practically tweakable and implementable on control area basis need to be developed. This is the motivation for the present work.

The cost of power depends on the source of power. Hence, optimization is required in scheduling power from various sources. The optimization studies need focus on the demand forecasting, Merit order Dispatching and the regulation of hydro generation by optimally utilising the water available in the reservoirs. Systematic approach integrating these factors can develop a model, which is suitable for day-to-day management of the power system operation in the most-economic manner. The model is however, specific to the control area of application, as most of the inputs are system specific. The methodology is however generic and can be customised for any control area.

1.7 SCOPE OF WORK

The scope of work is to develop methods for optimisation of the cost of energy delivered in a control area considering the constraints of maintaining quality of power supply and assessing the strengths and weaknesses of the power system encompassed by the control area and exploiting the opportunities.

The supply of electricity is governed by the rules and regulations in force and varies from country to country. The underlying rules and regulations assumed in this work are pertaining to those in India.

1.8 PROBLEM DEFINITION

The problem is defined as follows:

"To develop a method or set of methods by which the cost of power procured for delivery in a control area can be optimised on annual basis".

The cost of power varies from source to source. The major cost involved in the power procurement portfolio of a distribution utility is in the power purchases on long term basis and the proper planning of own hydro generation. Hence optimisation of power procurement on annual basis becomes optimisation of power purchases, realistic forecast of peak power and optimisation of hydro generation.

This being a real-world problem, pragmatic approach need be developed, which can be applied on a typical power system operation and shall consider all rules and regulations in force.

1.9 OBJECTIVES

The main objective is to develop a method by which the cost of power delivered in a control area is minimised, ensuring that the optimisation is on global basis and without compromising on the transparency of the process for review at each step of solution for critical analysis by the management.

More specifically, the objectives are:

i. To study the present optimisation methods followed in the Indian electricity sector for power procurement and to suggest further optimisation for ensuring availability and minimising the cost of power delivered

ii. To develop a method to conduct SWOC analysis (strengths, weaknesses, opportunities and challenges) of an electricity distribution licensee with respect to the power supply management in the control area so as to minimise the cost of power delivered on annual basis

iii. To develop a pragmatic method for estimating the power requirement for finalising procurement strategy for any control area

iv. To develop approach for "merit order pricing" of hydro generation and to apply merit order scheduling directly, avoiding rules of thumb in real time operations.

v. To formulate a method for optimisation of storage in the reservoirs minimising the chances of spillage

vi. To develop a practical approach for minimisation of cost of power delivered in the control area by developing a power procurement portfolio strategy.

1.10 METHODOLOGY AND OUTLINE OF THESIS

The ultimate objective of the problem is to minimise the cost of energy delivered in the control area without compromising on the quality and quantity (availability of power).

There have been a number of papers on the management issues of distribution licensees, optimisation of hydro thermal mix and generation scheduling. But most of the papers have approached the matter in different perspectives. Here the emphasis is on a holistic approach.

This thesis emerged in the attempt to a solution to a practical problem. The institutional issues of the utilities in the power sector is therefore captured in the solution methodology. The difficulties in adopting several solutions available in the research world are considered and addressed in this work. Further, while developing the methods utmost care has been taken to ensure transparency of the interim steps involved and easiness of modifications based on the changes in the government policies.

The approaches developed for conducting this study is summarised as follows:

- SWOC analysis (Strength, Weakness, Opportunity, Challenges) of the power system with the objective of optimising the power procurement cost over a control period.

  No published reference could be obtained for such SWOC Analysis of power system with the perspective of minimisation the cost of power delivered in the control area for a control period. On interaction with other distribution utilities of India, no such standard document is known to be available. The parameters to be considered in such a SWOC analysis are identified. The SWOC analysis of Kerala Power System is carried out with respect to the available generation and transmission capacity, constitution of load and other influencing factors as part of case study.

- The foremost requirement for optimisation strategy for reducing the cost of power delivered in the control area on annual basis (control period) is the assessment of the peak demand in addition to the energy requirement forecast. A novel method has been developed in this work.

- Optimisation of hydro generation on annual basis is possible by spill threat assessment and maximisation of storage to the active inflow period. Though several works were found on maximising the storage on daily basis, no studies were found with annual management perspective and with respect to spill threat analysis. Spill threat can be evaluated from the current storage, rate inflow and the rate of depletion possible. The inflow being very dynamic, the spill threat is also dynamic.

- Development of methodology for determining “ a merit order price” for hydro generation by segregating schedulable hydro and must run hydro on real time basis is required for merit order scheduling of power. The categorisation of must-run and schedulable depends on the present storage, current inflow, expected inflow in a sub control period, rate of inflow, spill threat etc. and involves reservoir modelling and inflow modelling.

- The optimum portfolio is then decided based on the outputs from the above methods.

The methodology developed is represented in Fig. 1.1

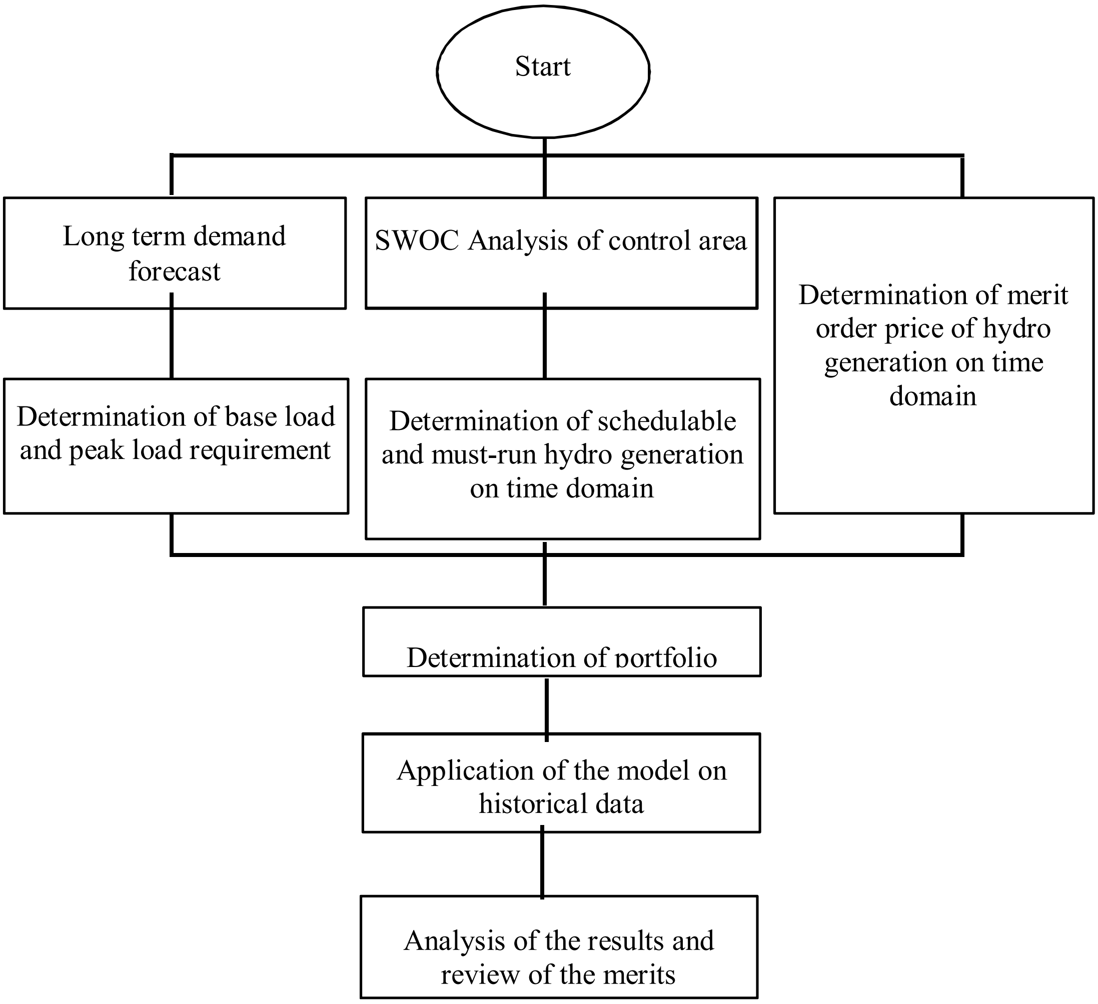

Fig. 1.1 Methodology

1.11 ORGANISATION OF THESIS

The thesis is organised as follows:

Literature review is detailed in Chapter 2. The literature review covers Load Forecasting in different time horizons, Economic Dispatch, Price Forecasting in the Markets, SWOC Analysis, Storage Optimisation etc. from published papers and from rules and regulations. Summary of limitations of various approaches has also been explained.

Chapter 3 explains the research framework. The limitations of the present approaches and the method developed in this thesis to overcome these limitations are explained in this chapter.

SWOC analysis is presented in Chapter 4. The methodology to be followed for the SWOC analysis of power system on control area basis is analysed and the major points to be considered are identified. The methodology was applied on Kerala Power System as a case study. The study of Kerala Power System, observations and mathematical interpretations are done in this chapter.

In chapter 5, the findings of the SWOC analysis of Kerala Power System is presented. The optimisation areas are identified as per the SWOC analysis and these are further developed for minimisation of cost of power procurement for the control area.

The need for long –term demand forecast and segregation of base load and peak load for the purpose of contracting supply of power is explained in Chapter 6. Case study with the data of Kerala Power System and the comparison of the results obtained are also explained in chapter 6.

The concept of merit order pricing of hydro generation by factoring the must-run and un-schedulable nature is developed in Chapter 7. The case study of Kerala Power System and development of statistical inferences are also explained. The analysis of spill threat is also developed.

Development of portfolio considering the above methods is detailed in Chapter 8. These include Purchase Decision, Hydro Generation Planning and Operation Planning Algorithm.

Chapter 9 discusses the results, interpretation and analysis. The benefits derived from the deployment of the methods developed in this thesis are explained.

The summary and conclusions are given in Chapter 10. The uniqueness of the thesis, summary, implications, and contributions to various stakeholders such as academic world, distribution licensee, regulators, government and the consumers of electricity are detailed in this chapter.

1.12 CONCLUSION

The methods developed in this thesis have emerged from a real-life problem. Hence, the problem was considered in totality and the methodology developed is also in totality with practical consideration. There has been no compromise in the requirements and constraints to suit any solution algorithm. In the process of development of the methodology simplicity, robustness and adaptability to suit any policy changes have been considered. The methods developed were successively introduced in Kerala power system and the results have been vouched.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

By the beginning of 1900s, Electricity was identified as the mother of all industries. In view of its impact in the development of the economy, the electricity sector had been supported by the government in all countries initially. The Electricity sector developed as vertically integrated industry under state control [1] considering the benefits that could be brought in by the economy of sizes in a capital-intensive long-life industry. As a publicly funded non-commercial entity, economic viability of the electricity industry was not at all considered earlier. Cost recovery was also not considered as a need to sustain the electricity industry. Over the period, the system became inefficient and the governments were not able to fund the sector any more. The electricity industry as such could not develop own funds for future development. This resulted in spiralling effect where the development of the country was hampered due to the stagnation of the electricity sector. The government-controlled entities in electricity sector had to be made commercial entities with economic viability. In India also, the power sector developed as disintegrated entities, became vertically integrated industry, and again mandated to operate differently as generation, transmission, distribution and system operation [2]. It has been identified that internationally, the major investment area in the sector will be transmission and distribution sectors [3]. The tariff for electricity at the end users' premises is of interest at macro-economic level. In India, the Tariff policy has been notified by the government and is being amended in accordance with the changes in the management of the sector [4]. Economic viability includes recovery of investment costs, operation and maintenance costs and making a moderate profit. This led to several researches in the operation and control of the sector to make it viable in every respect.

A changeover from a government-controlled regime to a market oriented commercial balance mechanism meant a drastic change in the price of electricity delivered and this led to the institutionalization of regulators for the sector. In India, these reforms have been put in place with the enactment of Electricity Act 2003 [5] and subsequent national policies. These policies are updated from time to time with amendments and additions.

The changes in the structure of electricity sector and the outlook of the business emerged from a lot of considerations having social impact other than the cost of energy alone. One important aspect adopted by all governments is the need for electrification of all households, which is based on the need for pollution control. The mounting pressure on climate control has also led to the policy development on the use of renewable energy sources causing least emissions of green-house gases in the production of electricity. Several research works happened during this period examining the possibilities of restructuring the electricity sector. Security of the electricity grid and the economy of operation were identified as the major objectives. The two major objectives of ensuring secure operation and most economical operation of the electricity grid is proposed to be achieved by the restructuring of the industry [6].

The opening up of electricity sector for competition has forced treatment of electricity as a marketable commodity and the changed scenario triggered a lot of scope for optimization in actual operation. One of the basic changes introduced in

Indian sector was the Availability Based Tariff for major generators and bulk consumers by the Central Electricity Regulatory Commission [7], [8]. Subsequently, the rules for operating the power system in the integrated mode was formalised and released as Indian Electricity Grid Code [9]. While inculcating the sense of competitiveness at macro level, it is common that the unorganised sector of electricity users are put into deep troubles. This is addressed with cross subsidisation in the earlier stages of policy changes [10]. Socio – technical issues on account of the policy changes along with the technical issues on account of the change in the power portfolio caused by increased utilisation of renewable energy has been a matter of concern in several countries and papers have been published [11]. In Indian context, the general outline of development is seen captured in the Electricity policy of the government [12].

Any optimisation has to have a control area and a control period. Normally, the control period is selected as the financial year as the cash flows and regulatory controls are exercised on this basis. However, for operation planning, energy portfolio management and study purpose, the impact of inflow to hydro reservoirs has also to be assessed, which is on water year basis, and may not coincide with the financial year. Hence, short term planning has a maximum period of one year. In this thesis, water year based plan is considered for hydro optimisation.

The tariff for electricity decided by the regulators is however determined for multiple years on account of the need for spreading some tariff components without giving a shock to the consumers. Several regulators approve multi-year tariff. In India, the National Tariff Policy in India has mandated multi – year tariff [12] for retail sale of electricity. Almost all states in India has followed the mandate and the

State Regulatory Commission implemented it in Kerala with effect from 2014 [13]. Further, the gestation period of the power plants being in the range of 5 years for thermal and even more for hydro, the impact of a generating station coming on commercial operation in the near future is to be factored into the energy balance and power balance computations. These factors lead to the conclusion that the medium-term forecasting has to be for a period of anything less than, say, 5 years.

Many research papers have been published in the area of power system operation optimization. However, most of the papers are confined to the level of optimization on the part of the constituent agencies of the power sector, viz. generators, and distribution companies and at utility level limiting the scope mostly to hydro thermal coordination. As the cost of energy delivered is control area based, ideal optimization scheme has to be on the basis of the total load generation balance for the control area in the control period as a whole. In this work, development of a scheme to optimize the portfolio management comprising of the electricity generated by own generating stations, long term contracts and short-term power purchases, factoring the market forces and hydro thermal coordination is attempted. The formulations in this work are basically based on the rules and regulations in force in India during the period from 2010- 2015. The changes in the policy, rules and regulations from time to time has affected the operation strategy of electricity sector and will continue to do so. The major research works in the area and the issues which are not addressed in them particular to the overall optimisation on the cost of energy delivered to the end consumer is reviewed in the succeeding paragraphs,

2.2 POWER SYSTEM STUDIES

Power system studies can be classified generally into the several core areas. Haque et al. [14] in their paper as early as in 2005 has identified the areas of studies. None of these areas are stand alone. The activities are highly correlated and any optimisation done in any area has its effect on other areas. Thus, for optimum operation of the grid in the most economic manner, it is necessary to have detailed study on each of the areas.

1- Load forecasting

2- Price forecasting and transmission pricing

3- Reservoir modelling and inflow analysis

4 - Economic dispatch by portfolio determination

There have been numerous studies in each of these areas. Several tools have been developed for optimization of operations also. Shahidehpour et al. [15] gives a descriptive narration on several tools that are used in power system operations. It is also worth noting that the regulation on transmission pricing and loss allocation in India effective from 1st January 2011 [16] had its roots in the academia and the implementation was also done in collaboration with the academic institutions. The present point of connection (PoC) mechanism for apportioning the transmission charges is based on a hybrid method, where the marginal participation and average participation of the loads and generators are determined. The basic presumption is that the efficient pricing of a service needs to reflect the marginal cost of utilisation of the underlying resources. Marginal participation is worked out on the basis of the change in flow of a line when injection at any node is increased by a small quantity, say, 10MW, with all other node data unchanged. Average participation method calculates the participation of agent, say i.e., by tracking the influence in the network of a transit between reference node (say, node i) and several ending nodes. In the hybrid method adopted in India, the slack busses are selected by using the average participation and the burden of transmission charges and losses on each node is determined by the marginal participation method. Thus, the power system studies have found application not only in the optimisation of operation of individual entities, but also in the process of formulation of rules and regulations in Indian context. It is also quite important to see that the industry has been always open to adapt the observations of the researches in the area and proactive in implementation. However, as the abstraction level of research increased and the complexity of operations increased, the adaptation has become a challenge for the power system engineers. This thesis is an attempt to bridge the gap in this context.

2.3 LOAD FORECASTING

Load forecasting is the basic requirement for planning the resources. In different restructuring models, the role of different entities differs. For instance, in the model discussed by Shahidepur et al. [15], load forecasting is associated with the functions of a GENCO (Generation Company). The optimizations possible for the generation companies are market based, where they can sell power to different entities and optimization of operational parameters. Optimising on Generation Company's perspective is effective, but such an optimisation may not yield in the global optimum of price at the delivery point in a control area on control period basis.

In Indian context, the distribution companies are expected to develop and maintain an efficient, coordinated and economical distribution system in their area of supply and to supply electricity [17]. Further, the state load dispatch centres (SLDC) and regional load dispatch centres (RLDC) are entrusted with the task of optimum scheduling of electricity from various sources in accordance with the contracts entered into with the licensees and the generating companies. Thus, the load dispatch centres and the distribution companies have to shoulder the responsibility of load forecast for the respective control area.

The contracts for power purchase are basically considered in three horizons – long, medium and short. The long – term purchases usually cover the life period of a power plant, say 25 to 35 years to cover the base load requirement, medium – term contracts to cover the seasonal variations in demand and supply and short – term contracts to cover the diurnal and weekly changes in the demand and supply. Accordingly, load forecasting needs to be considered in three different horizons depending on the application of the forecast results. Pillai [18] has described the basics of various forecasting tools at length. The degree of accuracy and the periodicity of studies also depend on this classification. Long term forecast goes into the commitment of construction of a new generating station or entering into a long term contract for power purchase. Medium term forecast primarily aids the fuel scheduling in the case of thermal plants and optimization of storage in the reservoir in the case of a hydro station. Short term forecasts vary from minutes to a week, i.e. 168hours. This finds application in scheduling of power and the real time and day-ahead market operation.

2.3.1 Forecast Methods

Many tools have been deployed in this area. Ekonomou et al. [19] and Chow, et al. [20] furnishes a good comparison of the various methods. Some of the frequently used techniques are Regression models, Kalman filtering, Time series models, Box

& Jenkins model, Expert systems, Fuzzy logic models, Neuro fuzzy models, Chaos time series analysis, Neural Network methods etc. The main reasons for such a large number of methods are summarized as follows:

- The results are to be necessarily as accurate as possible depending on the application of the forecast results. There is often a compromise with respect to the accuracy and the processing requirements. This stems from a commercial point of view as to the organization whether the error is within tolerable limits. The tolerable limits are control area dependent and within the control area, time dependent. The strategy for summer may not be the same as that for monsoon, for instance.

- Some forecasting attribute conditions are neglected in some methods leading to ambiguity at some point on the dateline when there are some external changes. The external causes may be policy changes by the government, change in the consumption pattern of the consumers, change in consumer profile, climatic changes and weather changes.

- Difficulty to find functional relationship between all attributes, variables and instantaneous load demand. Some of the models have built in several attributes. For instance, the rainfall in summer for tropical control areas as in Kerala may not be covering the entire area, and the change in the total demand on account of summer showers may show erratic values unless the weather condition is monitored in several points. In the test case, the attributes may be available, but practically feeding all such attributes may be difficult and expensive if not impossible.

- Difficulty to upgrade the set of rules that govern the load forecasting technique. The changes in the consumer profile, consumer behaviour patterns, policy changes affecting the availability of generation etc. may have to be incorporated at some point of time, for which the model should be amenable.

- Inability of some of the schemes to adjust themselves with rapid nonlinear system-load changes. The load behaviour is very dynamic and may be even so when the weather changes are due.

Among these, the Neural Networks have the advantage of taking many factors together and also to address the non-linearity. Neural Networks are reported to have delivered satisfactory models in several cases.

2.3.2 Short Term Load Forecasting

Short term usually refers to a period up to one week. The forecast results required shall have the differentiability of at least 5 minutes' duration. These results usually find application in Real time control which include system security and management of reserves

Economic dispatch

Unit commitment

Energy transfer schedules and market operations

The topic has attracted large interest in the academic field. Most of the methods suggested are applications of statistical methods. The concept of using weightages for determining the turning points on the demand curve for predicting half hourly demand by James et al. [21] was in application in National Grid Company, UK.

In the model proposed by Eugene et al. [22], calendar information, weather information, and some additional information along with an additive term when used is said to give good results. However, the availability of data for training the model is difficult to get practically. Even if data is available for selected places in the control area, they may differ from the average. This variation is more pronounced in tropical countries. Though it may be possible on an academic level to update these figures on the go, the practicality is questionable. The additional benefit accrued by providing such data is visible only in smaller control area, where the weather remains almost uniform throughout the area. Several researchers shortcut the issue by reducing the spread of the control area.

Application of Artificial Neural Network Simulation is by and large very popular in this area. Other tools used are regression, statistical and state-space methods, artificial intelligence-based methods, fuzzy system etc. Adepoju et al. [25] has presented a study of short-term forecasting with three-layer neural network and 5 neurons in the input layer. They selected the load of the previous year, load of the previous day, load of the previous week, day of the week and hour of the day as the 5 input values. Back propagation network with momentum and with adaptive learning rate was trained with pre-processed data after normalisation with sigmoid function. The results reported are 2.54% absolute mean error. The method is simple to use and is adaptable to any system, but the special holidays and other days of social importance are also to be added. These are not included in this work. Identification of similar day for special days is a tedious task when automated. Lack of sufficient data usually results in more errors on the forecast of such days.

A proper non-linear mathematical model should consider all parameters which may affect the consumption of electricity by the different consumer segments and aggregate them to arrive at the expected demand. These may typically include temperature, humidity, wind, nature of day, market activities which decide commercial load, possibility of a strike etc. It is not an easy task to list all such parameters and to evaluate the varying degrees of dependability for each of them. For instance, the impact of a serious match in a world cup, unforeseen death of popular public figure etc. may push the demand considerably high as has evidenced in Kerala power system [23].

2.3.3 Medium Term Load Forecasting

Medium–term load forecasting refers to the forecasting for one month to several months. The forecasting results can be confined to two general aspects – power balance corresponding to maximum and minimum demand during each control block and energy balance during the control period. For the purpose of power balance, outages of generators for maintenance are considered as the primary control so that simultaneous outage does not affect power availability. Transmission constraints are also considered especially with respect to counter flows[2]. Several papers reviewed were not considering the impact of counter flows in the transmission system.

For the purpose of energy balance, the typical control period is one year in view of the annual repetitive nature of some of the sources of energy and the consumption pattern. Most of the research papers are found to avoid several issues in convergence by taking smaller time windows, by which the constraints can be reduced.

Hsu et al. adopted annual energy balance equations in their model [24]. In this paper, the application of modified Grey Model is studied, so as to reduce the effect of reduced data for modelling. The study is based on Taiwan power system. Grey theory developed for systems characterised by poor information was applied by combining the residual modifications and residual artificial neural network sign estimation to improve the accuracy of grey model. The model was tested in the Taiwan system with the historical data from 1985 to 1998 for forecasting the demand of 1999 and 2000.The mean average percentage error (MAPE) for 1999-

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[22] Counter flow [71] is not actual power flow. The counter flows are considered when the power flow "as per contracts" and actual flows are considered in applications like determination of transmission capability, transmission constraints etc. As transmission constraints has got direct impact on the cost of power procurement, the counter flow concept is important in this analysis

2000 was found within acceptable limits. However, its application requires skill sets to interpret and analyse the differential equations in the grey model. This is not a practical solution for application in the industry. Further, the impact of the socio-political changes cannot be incorporated in the model easily.

2.3.4 Long term load forecasting

Long term forecasting covers 5 years to 20 years or more. The results are used by policy makers, planning engineers and economists. The forecast methodology for long term is entirely different from the other two. The long-term forecast has high dependency on government policy, level of industrialization, and other econometric factors. The methodologies followed are classified mainly as end-use models, econometric models and statistical model-based learning or a combination of these.

Econometric method is by and large fairly used in government level projections for administrative purposes [26]. The errors in this method may vary depending on several socio-economic situations. The consumption in different sectors such as residential, commercial, industrial, agricultural etc. is calculated as a function of weather, economic and other variables and then the estimates are assembled using recent historical data [12]. The government agencies have first- hand information on thee policy decisions, and the environment has to be matched to the policy change requirements. However, the forecasts are usually on the higher side in the power survey in India. The commercial impact of the error in projection may be huge for distribution utilities in the deregulated regime.

Integration of econometric approach in end-use approach introduces behavioural components also in the end-use methods [2]. However, both these methods are data intensive. Further the behaviour in different parts of the control area may be different. As the number of such load pockets increases, the data collection becomes tedious and also the quality of data gets compromised [10]. The statistical methods are increasingly used for long-term forecast also.

Multiple linear regression model using GDP, price of electricity and population as selected variables deemed most relevant for New Zealand electricity consumption is proposed by Mohamed et al. [27]. The independent variables were obtained from simple regression applied to the data sets of these variables over time. However, these variables are not fully independent and may be causing errors in the overall projection.

Multiple regression model was proposed by Ching et al. [28] for predicting the monthly demand under a wide range of weather conditions. The model is developed with the historical weather data and hourly demand data of UK for 15 years. The time series of monthly electricity demand was found to have a cyclic pattern. It is shown that the electricity demand has a strong inverse relation with temperature. A dead band where the electricity consumption was unresponsive to the temperature variation and a region of reduced correlation at extremely low temperatures were identified. The model takes the concept of degree-days to quantify the heating requirement during cold weather and cooling requirement in hot weather conditions as an alternative to plain temperature – load relationships. By incorporating socio-economic factors such as GDP and population growth, the model was able to give satisfactory results. However, the relationships in UK do not hold good for tropical area. Further, the model cannot be used directly where there are different weather conditions experienced in the same control area. Averaging of weather conditions do not give good results. Hence this model is not directly applicable in India and more specifically for Kerala control area. Thus the method is not generally applicable.

Brovold et al. [29] discusses about a method for hydro power formulation in a long-term expansion planning model. The purpose of the EMPIRE model described is to provide a long-term plan for timing, size and location of investments in generation capacity and inter-country transmission system in Europe. This uses a two-stage stochastic optimisation which formulates policy scenarios for the period from 2010 to 2060. The system is modelled country-wise and each year is modelled as 10 non-consecutive seasons with load generation balance for several hours in each month. Stochastic parameters account for uncertainty in demand and renewable energy sources. The method is specific to the European system. In this thesis, we have developed a method which is much simpler, but will also take care of the hydro storage optimisation.

Narasimha et al. [30] has made a detailed analysis of the Indian energy consumption pattern for the period from 1990s to 2000s. The energy intensity of the Indian economy in industry, transportation and agriculture has shown a decreasing trend since mid-1990s. The energy and GDP growth has shown a decoupling over this period. This trend is reported to be due to the shift in the economic activity towards services and efficiency improvement in energy intensive sectors. Energy efficiency improvements are fuelled by a number of factors such as high cost of energy, competitive pressures due to market liberalisation, implementation of regulations and standards for energy efficiency etc. Bureau of Energy Efficiency (BEE) [31], a statutory body functioning under the Ministry of Power with the objective of reducing energy intensity in Indian Economy, has been tightening the standards and imposing penalties for not improving the energy efficiency in various sectors. Recently, in 2016, the Central Electricity Regulatory Commission (CERC) has come out with the regulation on Energy Saving Certificates (ESCert) for electricity generating sector [32].

All these models are concentrating on energy requirement over a period. The peak power requirement for a control area is important for determining the capacity contracts the utility has to make. In developed countries, this is not a significant matter as the demand load factor is very high and the load curve is almost flat. [22,26,2]. In India also, the load curve of the industrialized states is comparatively flat. However, the load curve of Kerala is characterised by a sharp evening peak ramping [23]. Hence, forecast of peak demand is also as important as forecast of energy requirement. The forecast of real time power on large horizon is not seen attempted in most of the papers. A simple but efficient method for forecast, mainly to assess the power procurement requirement in future years was developed as part of this thesis [33], where the energy forecast and the load factor is used to assess the peak demand. This method has been put into use in Kerala for the past few years and found to be giving satisfactory results. In this method, the behaviour of Kerala Power system was studied in detail and the load curve estimation method has been used. The results were found to give good results as per the actual load profile observed in the subsequent years.

Optimum operation of the grid requires a stable and reliable grid. The transmission grid and the capability of the transmission system to carry electricity in either direction as per economic dispatch is important in controlling the market price and the cost of power procurement by a distribution licensee. The transmission planning criteria in India [34] and Indian Electricity Grid Code specifies the minimum requirements of the grid conditions. Faults in a power system are generally not preventable. Identification of root cause of outage on real time is essential for faster restoration. SCADA provides information of sequence of events, protection / communication system failures, and even corruption in acquired data. The period from the inception of the fault to the time at which it is restored represent a lost load for the supplying entity, which results in loss due to the lost load.

Fault analysis is a major area as the grid grows in size and complexity. As the capacity of the grid increases, the fault level also increases and the margin available for protection system narrows. Any attempt to reduce the fault level results in limitation of power flow through the available transmission assets. The reasoning involved in the analysis of cause- identification is typically heuristic in nature and is therefore a classification problem, which is approached through Logistic Regression, Neural Network (NN), Expert Systems, Fuzzy Logic, Genetic Algorithms (GAs), and Petri Nets [35]. The Petri Net modelling of the power system protection schemes provides the facility for hierarchical monitoring and evaluation of the system conditions to make a diagnosis. Lukomski et al. [36] describe modelling and analysing distributed systems. It is shown that by explicit representation of static structures, information flows, satisfied conditions and dependency relationships among transitions, the visualisation of system behaviour is possible. Logistic Regression [37] is a statistical parametric model to analyse binary dependent variables. It uses formalized model to exhibit the non-linear relationship between the variables. Main defect of Expert system method is its incapability of generalization and the difficulty of validating and maintaining large rule-bases. NN method uses input forward propagation and error backward propagation to search for a set of weights that can model the problem. The hidden layers improve the flexibility in ANN. It can also function well with noisy data. The main disadvantage of NN method is the long training period, which gets significant as the power network becomes large. General Regression Neural Network in feed forward topology, the Probabilistic Neural Network, Adaptive Neuron-Fuzzy methods and the selective back propagation algorithm are the methods used to reduce the training period.

2.4 ECONOMIC DISPATCH

Economic load dispatch means meeting the demand at the lowest possible cost (including generation and transmission charges and transmission losses) subject to the constraints in generation and transmission and the obligations to keep security and stability of the grid. Thus, economic load dispatch problem is solved as a minimization problem which minimizes the overall cost, by allocating the forecasted demand over the available generators simultaneously satisfying the spinning reserve requirements and operational constraints [38]. The unit commitment is done for short duration, say for a day and a week. Several numerical optimisation techniques have been applied for unit commitment problems.

Lagrangian relaxation method, Linear Programming (LP) techniques, Dynamic Programming (DP), Beale's Quadratic Programming, Newton-Raphson's Economic method, Lagrangian Augmented Function, Mixed Integer programming etc. are mostly used in this area. Typically, the economic load dispatch is a non-convex optimization problem, and Lagrangian Relaxation cannot be done directly. The LR method temporarily ignores the coupling constraints and solves the problem as if they did not exist. The LR decomposition procedure generates a separate problem by integrating some coupling constraints into the objective functions through penalty factors (Lagrangian multipliers). The Lagrangian multipliers are determined iteratively. Estimation of the Lagrangian multipliers relies on sub-gradient or heuristic method. Even though the optimum solution to the individual sub problems can be easily found out, the global optimisation is not guaranteed due to the non-convexity of the problem. Cheng et.al [38] incorporates GA (Genetic Algorithm) into Lagrangian Relaxation to update the multipliers and improve the performance of the LR method.

A method of solution using Lagrangian Relaxation and Augmented Lagrangian for minimising the operation cost over a two-day horizon with one hour time resolution was attempted by Rodrigues et al. [39]. The problem is decomposed into thermal, hydro, hydro thermal and hydraulic. Hydrothermal sub problem considers demand reserve and transmission constraints. Reservoir constraints are modelled in hydraulic sub problem. Augmented Lagrangian is applied to find a feasible primal solution then. The model does not differentiate between the non-constrained special distribution of hydro generation. Thus, the solution cannot be said to be a global optimum.

Chrobak [40] propose hydrothermal scheduling problem solution using hierarchical decomposition into hydrothermal coordination problem (HCP), Unit Commitment problem (UCP) and economic load dispatch problem (ELDP). HCP is further decomposed into long, medium and short term models and is coupled in time. UCP determines which thermal unit will be running during the scheduling period. ELDP finds out the optimal allocation of power demand on the running units, satisfying the load generation balance and the operational constraints of the running unit. These are implemented by Genetic Algorithm (GA). This approach will not bring in the optimisation of the operation of the control area on control period basis as there is no provision to provide variable cost factor for hydro generation.

Zhao et al. [41] attempts economic load dispatch problem as a multi objective optimisation problem with non-commensurable and contradictory objectives. The improved multiple particle swarm optimisation method proposed is population based, uses external memory and geographically based approach to maintain the diversity of sets of pareto-optimal solutions and uses a fuzzy based mechanism to extract the best compromise solution. However, the approach has taken only economy, minimal environmental impact and system loss as the objectives, which is a serious limitation.

Sumait et al. [42] uses a pattern search algorithm for solving ELD problem. It is a derivative free algorithm. It starts with a sequence of points that may or may not approach the optimal point. The algorithm starts by establishing a set of points, called mesh. The mesh is formed by adding the current point to a scalar multiple of vectors called pattern. If a point in the mesh is found to improve the objective function, it becomes the new current point at the next iteration. Constraints are handled by Augmented Lagrangian. The variable bounds and linear constraints are handled separately from non-linear constraints. This method does not recognise the possibility of variability of the hydro generation on control area basis, which can optimise the overall power purchase cost for the control area on annual basis.

Solutions to several power system problems have been attempted using “decision trees”. Economic load dispatch problems are solved in general as optimisation problems. Many of these methods are sensitive to starting points and may converge to a local optimum or diverge altogether. Linear programming methods are fast and reliable, but have the disadvantage of piece wise linear cost approximation. Non-linear programming is complex and has convergence problems. Newton based methods cannot handle more inequality constraints. Decision trees is a powerful data mining tool designed to face classification problems, dividing the output variable space by the evaluation of partition rules developed front he explanatory variables. The output variable is classified by the explanatory variables rules that give the maximum quality to the decision tree. Lobato et al. [43] proved the versatility of decision trees by applying them in various applications. The interpretability of the results and availability of probability values without assuming normal distribution are the major advantages of decision tree method. The hydro pricing on annual basis and optimisation by shifting the generation in a time frame of a few months is not attempted in this paper.

One of the early references on economic load dispatching considers optimum shift with regard to contingency conditions of active and reactive power scheduling [44]. In this paper, Farag et al. presents a method to determine the optimal shift in power dispatch related to contingency states or overload situations in the system. The approach was that the additional cost involved in shifting generations is minimised. This approach is however not suitable now as it cannot consider the market component and also does not factor the price of hydro power, a new idea developed in this work.

With the opening up of the market structure in power industry, the conventional system operation strategy to balance load and generation on merit order alone has given up to portfolio optimization strategies. In a deregulated environment, multiple markets of different scales exist and each market may have multiple instruments. The open access of transmission system in India has been regulated by the Central Electricity Regulatory Commission and the regulations are being amended as the market matures [45]. Accordingly, the Indian electricity market consists of the following major portfolios:

- Long term contracts which have a contract period exceeding 12 years
- Medium term market which covers 5th month to 41st month
- Short term market is generically applied to contingency markets which can schedule power in one-hour notice as well as advance short term open access covering upto 4th month.
    - Normal short-term open access market is usually arranged through traders. However, bilateral trades co-exist. The sale – purchase agreements are entered into by the distribution companies among themselves or generation companies directly with the distribution companies or even with the consumers.
    - In 2016, the Ministry of Power has come out with the DEEP portal [46] (Discovery of Efficient Electricity Price) for streamlining all such transactions and to provide a uniform bidding platform. This platform also provided guidelines for bidding and provides a reverse bidding window for efficient discovery of price.
    - Term – ahead markets are operated by open auction mechanism in the power exchanges. As per the present regulations, this market operation is permitted for a period of 11 days [48, 49]
    - Day –ahead market operated through power exchanges is a double-sided closed auction. This market has flourished in India and is now accepted as a common platform for utility scale sale / purchase as well as consumer scale sale / purchase. CERC continues to monitoring the market operations [50].
    - Contingency market operated through the power exchange platforms, which function on 24×7 basis. This market is however very shallow due to the difficulties in getting approval from various agencies concerned
- Ancillary market operation in India is with limited scope now. It is not permitting the participation of the generators other than those whose tariff is determined by the central electricity regulatory commission. The issues are related to settlement of the energy scheduled, where fixed charges and variable charges are easily discernible and the capability can be independently assessed. [51]
- Day ahead market operated by generators having surplus on account of original contracted entities giving up the requirement in advance [52]. This market is also very shallow and the energy transacted is only a miniscule of the total energy transactions from such generating stations.

For the control area management professionals, all these markets are available and the depth of each product in the market varies dynamically. This results in scope for portfolio optimization for control area management. As with any portfolio optimization, the risk mitigation becomes the benchmark in such cases.

Jun et al. [53] proposes a midterm power portfolio optimization problem with risk management. The time horizon considered in this paper range from one month to one year. They have proposed Surrogate Langrangian Relaxation to solve the problem by relaxing the expected load obligation constraints and individual instrument constraints. The method is however computationally heavy and the computation time increases linearly with the number of portfolios and the time span. The method is claimed to obtain near optimal solution. Some background knowledge of the mathematical modelling is also required in adapting this method in real life. The scheme suffers from the disadvantage of sub – optimal results on annual basis and also complexity for use in everyday life by the system operator.

Principles and guidelines for effective energy sourcing is discussed by Alfredo et al. [54]. This paper considers two energy markets – spot market and bilateral contract market. Though the scope is limited, the paper proposes a novel strategy for the energy sourcing from user perspective based on decision theory. The solution for optimal decision is derived from the statistical characteristics of the spot market and load and the contract prices. The decision analysis is based on a set of mutually exclusive alternatives. The spot price volatility and load forecast error are considered as the primary uncertainty. Though this method is applicable for optimization of control area power supply cost, the method is not scalable to include all sources of power as existing now. Hence there is a need to refine the approach for meeting the present-day needs.

Najafi et al. [55] proposes harmony search algorithm for solving unit commitment problem. Optimization of unit commitment goes directly to minimize the cost of power scheduled. Harmony search algorithm is based on natural musical performance process when a musical search for a better state of harmony. The application of this algorithm results in a global optimal solution that is determined by the objective function. The objective function is minimizing the total cost which includes fuel cost, start-up cost and shutdown cost. The start-up cost is dependent on the condition of the machine, viz. whether it is a cold start or hot start. Though the method is scalable with respect to the number of machines and the load, the scheme suffers the inherent drawback of non-modelling of hydro generation possible based on the storage and the expected inflow.

Zhai et al. [56] proposes a solution for optimizing the short-term generation schedules for the power systems using quadratic programming. The model considers nuclear machines first, then hydro generators and then coal based generators in consideration of the limitations of generation change in the nuclear machines and non-polluting renewable nature of hydro generation. It uses two models – model 1 to solve the problem of allocating hydro loads and thermal loads and model 2 to solve the problem of optimal power dispatch within hydro machines and coal fired units. The solution methodology does not consider the market power sources and hence not adaptable in the present context. Further, the capability of hydro sources to respond immediately to the changes in the demand as well as market conditions is not considered here. The stated benefit of pollution from coal-based stations is also to be reconsidered when sudden change in output is required.

2.5 PRICE FORECASTING

Load forecasting is conventionally identified as an essential tool for optimum system operation. However, in the open market system, the market operation has assumed a significant role in economy of operation. The power purchase cost is the major cost component in the price of power delivered within the control area. Economic operation of the grid requires unit commitment in merit order, for which the price anticipated in the market also needs to be predicted. Especially in the case of hydro schemes with storage reservoirs capable of year-round hydro generation, the price forecast for the different periods in the year assumes significance.

The Price forecasting is categorized into

Short term – This is applicable for a period which covers upto a week or so. The figures usually go into merit order dispatch decisions and day-ahead purchases/ sales

Medium term – The applicability period is from a month to a year. The forecast values are the key factors in arranging fuel, contracting power on medium term basis, tackling issues like expected transmission constraints, planning annual outages of generators and transmission corridors.

Long term – The forecast is basically based on economic driving factors of the country, international factors. These are used by planning engineers in planning new projects, arranging long term tie ups for fuel, transmission capacity enhancement etc.

The electricity market has special characteristics such as dynamic behaviour, split second transportation, inelasticity in production and consumption, multiple seasonality behaviour, diurnal variation in demand and supply leading to spot prices varying continuously, calendar effect, political and social effects, non-linear behaviour etc. [6]. These characteristics lead to high volatility and unexpected prices discovered in the market. All these make the price forecasting one of the most challenging tasks. Accurate forecasting is necessary for the power suppliers to maximize the profit and for the customers / distribution companies to minimize the cost of power purchase. The forecasts are equally important for all players in the field, such as generator, transmission companies, distribution companies, system operators, traders etc. Successful operation requires appropriate bidding strategies. These strategies depend on time. Much data is available and the analysis of these data and the analytics methods are numerous. There are two different approaches in the analysis. The first method analyses the constraints in generation, transmission and load based on which a price forecast is obtained. This method also factors the behavioural strategy of suppliers and buyers. The second method is the deployment of statistical tools, where it is assumed that the technical issues are also captured as events in the time series.

Auto Regressive integrated moving average (ARIMA) method has been proposed by Javier et al. [57] for day – ahead forecast of 24 hourly energy rates. In this method, first a class of models is formulated on the basis of some hypothesis. A model is identified for the observed data and the model parameters are estimated. On validation, if the estimate is correct, the model is ready. The process of selecting model is repeated till the estimation becomes correct. It is reported that the average errors of the models developed from Spanish market was around 10% and that for Californian market was around 11%. The modelling is system dependent and has to be done for each system. The major drawback of the method is that the accuracy of forecast depends on the accuracy of the data supplied for training and further, it presumes that there are no major changes in the hypothesis made. For instance, construction of a major trunk line between two constrained sub grids could revolutionise the market clearance rates, which will not be captured by such a system. The method is applicable satisfactorily for next day price forecast.

Mirko et al. [58] developed a probabilistic method for determining the price range for day-ahead market price considering the previous volatility values. Price volatility is a measure of the dispersion in prices observed over a time period. The strong relationship between price and load for moderate load variations is considered for evaluation of the forecasted price range. Only two inputs are used in the method – previous prices and load data. These are available with good accuracy. As inputs like weather are eliminated, the model is simple to use. However, the model may fail under conditions of special occasions like a major sports event, festival, hartal etc.

Generalised Auto Regressive Conditional Heteroskedastic (GARSH) methodology was applied for price forecast by Garcia et al. [59]. It considers the moments of a time series as variants. The error term, which is the difference between the real value and forecasted value are assumed to be serially correlated and is modelled by an auto-regressive process. Thus, GARSH measures implied volatility of a time series due to price spikes. The method is suitable for price forecast on day-ahead basis. However, the method is not suitable for the non-linearity conditions introduced by the transmission constraints as that happens in India nowadays.

Fleten et al. [60] proposed a stochastic linear programming model for constructing piece-wise linear bidding curves to be submitted to Nord pool, the Nordic power exchange. The optimisation adopted assumes that a price-taking retailer will reduce the load when prices are high and vice – versa. In Indian conditions, the concept is different as the generators having firm PPA (Power Purchase Agreement) is more and also that the marginal capacity available with such generators do not cause any financial burden on them other than the reduction in profit. However, the method can be modified to suit the Indian conditions by transferring the role of price taker retailer to the distribution licensees having internal generation. But, in this case also, high renewable penetration states pose difficulty in adapting the method.

Effective prediction of market clearing price and confidence interval estimation using neural networks with Extended Kalman Filter as an integrated adaptive learning and Confidence Interval estimator is discussed by Zhang et al. [61]. Through linearization, the extended Kalman filter is widely adopted for state estimation of non-linear systems. However, the method has excessive computational requirement.

From a supplier's point, the price forecasting is for bidding purpose in the market. Song et al. [62] proposed a Markov decision process, which is a discrete stochastic optimisation method. They have proposed a discrete state and discrete time type Markov decision process (MDP). The market clearance price is determined by the day – ahead load forecast and the bids from the suppliers. The model is said to resemble the market structure in England and New Zealand. The model however does not mention about the market splitting which is common in India. The handling of transmission constraints in the market operation is different in Indian context.

Pindoriya et al. [63] suggested adaptive wavelet neural network for short term price forecasting with Mexican hat wavelet as the activation function for hidden layer neurons of feed forward neural network. It has been reported that the results gave good results compared to wavelet ARIMA, multi-layer perceptron and radial based function neural networks. The method is however computation oriented and the user should know where to start and stop.

Zhou et al. [64] proposes a stochastic process theory where prices are considered as nonstationary stochastic time series. Price forecasting is obtained by the solution of the auto regressive integrated moving average (ARIMA) model. Based on the real market records and corresponding forecast values, the model error series is used for adjusting the forecast prices and improving the accuracy. With Californian power market simulation, the authors have claimed satisfactory results. A three layered feed forward neural network trained by Levenberg –Marquardi algorithm is proposed by Catalao et al. [65] for forecasting next week electricity prices. The accuracy is evaluated with Spain and California markets. The market behaviour in India is quite different. One major point is that Indian Electricity consumption is still having a positive slope, whereas most of the European markets and California markets are showing flat load growth for several years with slight negative slope recently. The models applicable there will not be suitable here.

Doulai et al. [66] proposed a fully connected MLP neural network using BP as the learning algorithm and the Tan – Sigmoid transfer function as the activation filter for price forecasting. They developed models with minimal weather information, using forecast temperature and using weather information. The study was done in Australian power market and they have shown that the accuracy increased considerably when the weather data was also used. The weather parameters used were temperature, humidity and wind speed on ½ hourly basis, which meant 48 data per day. However, this method will suit only markets with little change in weather parameters across the geographical spread. Definitely, in India, this will not work.

An attempt to predict both demand and price of electricity on day-ahead basis using a three-layer back propagation model has been proposed by Xu et al. [67]. It is mentioned that the model gave good results with the data from Queensland electricity market in Australia. The demand was also included considering the correlation between price and demand. Transfer function chosen was tangent sigmoid function. The forecasting is done in two steps, first the demand is forecasted and it is used along with other parameters to forecast the price. The model is giving only hourly price curve. Adaptability to Indian condition with frequent transmission constraints which results in market splitting is not covered in this approach.

The forecast methods are categorised into different modelling strategies. These strategies are either used as such or combination of these models is used. [68]

- Multi agent models, which include multi agent simulation, equilibrium, game theoretic etc., simulate the operation of a system of heterogeneous agents interacting with each other and build the price process by matching the demand and supply in the market.
- Fundamental methods which models the physical and economic factors affecting the price of electricity
- Stochastic methods which models the electricity price only and works with statistical methods
- Technical analysis which are either direct applications of statistical techniques of load forecasting or power market implementations of econometric models
- Artificial intelligence techniques which combines learning, evolution and fuzziness to create near world behaviour

Most of the published literature depicts either one or combination of these techniques. In Indian context, in day-ahead market, the aggregation of supply and demand is done and the price discovery is basically through auction. This process is done by the power exchanges, viz. Indian Energy Exchange (IEX) and Power Exchange India Ltd (PXIL) [69]. This is in contrast with the ISO (Independent System Operator) in some countries. The bidding in the day – ahead market is double sided anonymous bidding. The buyer and seller are not visible to each other and there is no one – to – one agreement between buyer and seller. Seller sells to the sales pool and the buyer purchases from this pool. Once the unconstrained market clearance price is arrived at, the constraints are applied and market splitting if necessary is done [70]. Most of the causative agents for market splitting are often known apriori. However, constraints occurring due to forced outage of transmission lines and outage of generators in critical locations may not be known upfront to the market players. [71] In India, this has been quite common for the power market in Southern Region till about 2015 second half and in Northern Region even now. Congestion could result in price hike in some regions and abnormally low prices in some other regions. Generators are often constrained to sell power at rate lower than the actual variable charges in consideration of the additional expenditure that could be incident due to heat rate correction and increase in the auxiliary consumption. The heat rate correction for 55% load factor is estimated as 3% for supercritical units and 6% for subcritical units. The degradation in auxiliary energy consumption is estimated as 1% for 55% load operation [72].

The bidding strategy has also been a major study area in research world. Philpott et al. [73] proposed simple optimisation models with particular reference to the Norwegian real time market known as regulating market. The authors analysed the opportunities of speculation in the up-regulated and down regulated scenarios. Effectively, it turns out to be a strategic game in two stages played by the generators and purchasers. The major purchasers pursue a risk neutral approach and purchaser's bid remains close to the demand that they predict. The bidding strategy is different for different categories of consumers. For instance, for a continuous process industry, non-availability of power for even a small duration could result in substantial loss in production and the associated loss. The price discovery in the auction market could be very high in such cases [74]. The difference in the elasticity of demand among different consumers is the major factor affecting the price discovery in the market.

2.6 SWOC ANALYSIS

In order to assess the portfolio optimisation further, it is necessary to analyse the Strength, Weaknesses, Opportunity and Challenges (SWOC) of the control area under study. This is similar to the SWOT analysis developed by Albert Humphrey of Stanford Research Institute in the 1960s as a common tool used in strategic planning sessions [75], the difference being that the threat is replaced with challenges. It involves specifying the objective of the business venture/ project and identifying the internal and external factors that are favourable and unfavourable to achieve that objective. Setting of objectives is done only after SWOC Analysis, which form the Challenges for the business. Strength and weakness are internal characteristics of the power system and the opportunities and challenges refer to external factors which include government policies, prices of fuel, availability of fuel etc.

SWOT analysis has been recognized as an effective method for portraying the internal context in terms of strengths and weaknesses and scouring the external contexts as opportunities and threats for a business [76]. In this paper, Markovski et.al sheds light on the energy sector of Macedonia and proposes a portfolio of actions for sustainable development. The approach taken is participatory (bottom up component) complemented with a study of relevant strategic and planning documents, legislation and statistics (top down component).

SWOT analysis is specific to the systems being considered. Dasappa [77] discusses the SWOT analysis with respect to biomass generation potential development. The author has compared the strengths and weaknesses of the fossil power and biomass power. The opportunities and threats are also discussed so that the business model can be evolved. The paper is specific to biomass generation.

Raffael [78] has used identified SWOT analysis for evaluation of the effect of renewable integration to the grid and the concept of virtual power plants, micro grids and energy hub in the approach to increase the integration of renewable resources. However, the analysis and findings are with respect to renewable integration and hence the proposal suffers from the issue of local optimisation.

In an effort to develop a strategic planning framework for distributed generation, Lokesh et al. [79] uses SWOT based strategy for generating sustainable competitive advantage in order to develop market for renewable sources. Analytic Hierarchy Process (AHP) and Analytic Numerical Process (ANP) tools are used in their study. AHP gives overall ranking of the alternative strategies. The stress given is from generators' point of view.

Guido et al. [80] discusses the potential of SWOT analysis in Public Support System (PSS) for planners and system developers. PSS are a subset of geo – information technologies dedicated to aid those involved in planning to explore, represent, analyse, visualise, predict, prescribe, design, implement, monitor and discuss issues associated with the need to plan. The SWOT analysis has shown the useful applications of the PSS in planning.

The limitations of SWOT analysis is discussed by Erhard [81]. According to the author, SWOT analysis rests on shaky suppositions that every strategically significant feature of a business' internal and external context can be categorised neatly as favourable or unfavourable. The SWOT does not shed lights on how noteworthy particulars are to be identified and classified correctly or how strategic implications are to be derived. SWOT framework does not readily accommodate trade-offs. He suggests DOE (Defensive/ Offensive Evaluation), which is more focussed on theory driven than SWOT Analysis. However, it is observed that SWOT analysis is sufficient in the present case as the number of peers is less and competition is not severe.

London Economics International LLC [82] has discussed the SWOT analysis of Nova Scotia power sector for facilitating regulatory and legislative initiatives. There are several parallels with Kerala power system. Nova Scotia power system is relatively small and dominated by the incumbent utility. It is partly liberalised with whole sale competition allowed. Nova Scotia has very limited interconnections with other markets, a case similar to that of Kerala. In this thesis, the SWOC analysis of Kerala Power System is done.

Dr. D. Shina [83] has given a concise history of the Kerala Power system. The Kerala power system emerged from a few oil engine generators in major towns to a hydro based power system by 1940, about 30 years after the commercial use of electricity happened in the world. The paper however does not consider the impact of the central sector projects and development of inter-state transmission system and its advantages and disadvantages.

Annual reports of KSEB [84] provide insights into the history of power sector development in Kerala. The details clearly depict the growth of Kerala power system over the years. Prayas group, Pune has prepared and published several studies, among them the studies on the power sector in each state in India is also presented [85]. The state was a power surplus state selling power to neighbouring states till about 1980s and the reversal of the situation happened with the non-take off of Silent Valley project slated to start construction in 1970s. Another significant factor mentioned is the consumer mix. In 1970s, the energy consumed by high voltage industrial sector was as high as 64%. At present the consumption of industries is roughly 22% of the total energy consumption in the state [86].

The Strengths, Weaknesses, Opportunity and Challenges of the power system under study are not static. They vary over the time and depend on internal strategic changes and extraneous reason including national policies, rules and regulations. The policy decisions by the governments evolve from a number of socio – economic factors. These extraneous factors have a great impact on the opportunities and challenges for the power system operation in achieving overall economy of operation.

2.7 ASSESSMENT OF PEAK AND BASE POWER CONTRACTS

The distribution utility is bound to identify sufficient resources to meet the requirement of its consumers under all the conditions. In Indian context, the distribution licensee is mandated to provide electricity to any applicant in its area of jurisdiction [87]. In a truly liberalised set up, the distribution company has interest only to maintain such consumers who are paying more than the cost of supply. The Act 2003 enables such consumers with the flexibility of choosing the supplier through open access, while mandating the distribution company to feed any prospective consumer in their area of operation, subject to regulatory checks. This is intended to improve the efficiency of service by the distribution licensees. Traditionally, the distribution companies take their own measures to construct sufficient generating stations to match with the load in their control area. As there had been generating stations set up in the central sector in India to take advantage of economy of sizes, the states were given proportional share in these stations. These were considered as par with the internal generation capacity. The exercise was to meet the load-generation balance on long-term basis, which requires long-term load forecast. The long-term forecasts adopted in India suffered from significant variations, resulting in over construction of generation capacity at times. Several of the measures described here are considered in Indian context in general. The power survey reports of CEA [88] forecast the annual consumption for the entire country and also for each state. However, mere adoption of this report is not being attempted by many agencies. The life of a power plant being 25-35years, factors like policy changes, availability and cost of fuel etc. are prominent risk factors. Some generating stations have been affected and are performing below the expected levels and even down to zero annual plant load factor [89]. Such non-performing assets add the financial commitment of the beneficiary distribution company. Hence alternate measures for long term load forecast was considered in this work, which is also used for portfolio decisions on long term basis.

Assessment of demand encompasses the assessment of real time power requirement and the control-period energy requirement. Though the latter is only a time integration of the former, the assessment methods are quite different. The prediction of energy requirement is rather easy and matches better with the actual than the real time power requirement projection. Several forecasting methods have been discussed in research space. Combined Forecasts with Changing Weights for Electricity Demand Profiling is proposed by James et al. [20] using a cubic smoothing spline. The method proposed was for day-ahead forecast for market operation. However, on detailed analysis, it was observed by us that the concept of demand profiling could be extended to long term forecasts also, but not using the method suggested in the paper. The concept of cardinal points and the curve fitting for profiling has been used in this project.

Zaid et al. [25] discusses a multiple linear regression model for the forecast of electricity for New Zealand. The model assumed GDP, price of electricity and the population as the most significant factors affecting the electricity consumption. The total consumption was split into domestic and non-domestic for this study. It has been established by the authors that the multi-collinearity issues were studied in detail and the parameters were selected accordingly. It has been observed that in India, the diversity among the states in respect of life style, industrialisation and urbanisation is drastically different and that could be one of the reasons for the gap between National Power Survey of CEA [88] and the actual consumption.

Hsu et al. [90] discusses the application of artificial neural networks in regional forecasting in Taiwan. Taiwan is divided into four regions and 15 years' data was taken to train the ANN model. Testing was done on 3 years' data. The four regions have been taken according to the administrative divisions. The input pattern was modelled by three neurons – regional GDP, regional population and regional highest temperature. The hidden layer had two neurons. With this model, the forecast for the next 10 years is said to be made with satisfactory results. This approach has several parallels with our work. We have also considered geographical boundary of the states as the demarcation of control area, which is even otherwise recognised in India for grid management. We have also aimed to forecast at least 10 years' demand. However, for planning the source of power for future use, the demand profile itself is required, which is not attempted by Hsu et al. in their paper.

Econometric and end-use methods are usually adopted for annual load forecast. For optimizing purchase decisions and scheduling of power from various sources, load profile on diurnal basis and annual basis has to be derived. Several techniques have been developed and deployed for estimating the load profile on short-term basis. The method proposed by James et al. and Vaccaro et al. can be applied for determination of the demand and price forecast, but their application gives good values in short term only*,* Xu et al. proposes ANNs for price and demand forecast in deregulated power market. However, load profile based on these short-term load forecasting methods using relaxation techniques and ANN methods is not appropriate in view of the time span considered for arranging power purchase contracts.

The Central Electricity Regulatory Commission (CERC) issues regulations on terms and conditions of tariff gives the general principles followed in India for tariff setting [7, 71,72]. The regulations are in line with the national tariff policy issued by the government of India. The tariff is fixed on cost plus approach for the generating stations whose tariff determined by the regulators. These are fairly stable over long term. The market forces in power sector has to be seen on two perspectives – one on long term basis and the other on short term basis. The long-term prices almost converge to the regulated price, but the methodology applied for computing the fixed (capacity charges) and variable cost separation is different [91]. The rate of power in the short-term market can be studied from the daily data given in the web site of Indian Energy Exchange, which is the largest exchange operator in India. The market analysis is also done by the Central Commission and monthly report is published in their web site. A few other agencies also, such as India Power Trading [92] and Independent Power Producers Association (IPPAI) [94] are also furnishing insights into the anticipated availability of power and the likely market power exerted by each. For the analysis with reference to Kerala demand and generation pattern, the details are collected from the website of Kerala State Load Dispatch Centre [89]. Additional details which are deciding factors on the price of power are available from the web site of Southern region power Committee of Central Electricity Authority [95]. Market related information is further collected from the reports section of Southern Region Load Dispatch Centre (SRLDC) [96] for intra-regional network. For inter – regional network, Market information tab of National Load Dispatch Centre (NLDC) [97] gives the information. The transmission capacity for the next three years is updated by the central transmission utility (CTU) [98] whenever there is any addition of transmission elements. Other sources of consolidated data for carrying out the analysis are Kerala State Electricity Regulatory Commission (SERC) [86], web site of the central electricity authority of India [88] where periodical reports are consolidated and uploaded.

2.8 STORAGE OPTIMISATION

H Ahlborg et al [99] discusses the strategies to be adopted to achieve economic viability of hydro generation on public-private-community partnership basis, which gives a clear picture on station level optimization. Though the methodology links to market behaviour also, the paper does not consider a global optimisation on the cost of power supplied over a control period.

Tahanan [100] gives a good review of literature pertaining to unit commitment. Unit commitment problem aims at finding the optimal scheduling of units on system – wide merit order and constraints. In a hydro – thermal system with spatial variation in the distribution of rain, the market price varies with the availability of hydro power. This factor has to be considered in the attempt to arrive at the optimum unit commitment. However, this paper does not consider the optimum storage management for market operation and hence the unit commitment for economic load dispatching mentioned is not a global optimum.

Harmony Search algorithm for unit commitment problem was proposed by Najafi et al. This method is claimed to be easy to use compared to the evolutionary methods. The HS algorithm includes a number of optimisation operators as different vectors. A new vector is then developed by selecting the different components of different vectors randomly in the harmonic memory. Thus, the algorithm is reported to be taking care of the global optimisation rather than converging on the local optimisation. But this method is also based on the hydro generation capability as known to the algorithm. It does not take care of the possible changes in the inflow to the reservoirs within the control period. In other words, it is not linked to storage management, which is very important in the optimum utilisation of the resources in the control period. In this thesis, we have included the storage optimisation also, which improves the overall reduction in the cost of power supplied during the control period.

Arce et al. [101] developed a model for optimum scheduling of Itaipu, world's second largest hydroelectric plant. The paper is highlighting the trade-off between start-up/ shut down of generating units and hydro power efficiency and variations in tailrace elevation, penstock head losses and turbine-generator efficiencies for optimisation. The installed capacity is 20GW, more than five times the peak demand of Kerala as on date. In the best year, they have achieved annual load factor as high as 80% [102]. In this attempt also, storage optimisation is not seen attempted, possibly because of the high design load factor, which does not warrant any optimisation on the storage maintenance, but more stress is given to the start/ stop costs. The authors have taken US$ 3/MW as the start-up and shutdown cost for the station, the details of which are not shared. In our environment, this approach is usually taken for thermal machines.

Arellano et al. [103] discusses the market power exercised by hydro generator on account of the storage available. It is shown that even where prices are set to the marginal costs, by altering the generation portfolio, generators can exercise market power and they can earn rents by increasing the share of peaking technology in the generating portfolio beyond its welfare – maximising level. The strategy could raise the price of power paid by the exchequer as the peaking station stretches operation beyond the essential period with the capacity charges unchanged. This is not a case of profiteering, though. In the case of generating stations constructed and maintained by the distribution company itself, the normal design could be with respect to the inflow received with 75-90% confidence, depending on the site. This means that such generators may have the flexibility to have extended operation and not limited to the peak shaving function alone. Another case is the combined irrigation and power generation projects, where large upstream generators would be built and maintained by the electricity utilities. The storage management proposed in this thesis is exactly about the utilisation of such surplus in reducing the overall power procurement cost of the distribution licensee and the ways and means to maximise the availability of such generation capability.

Christoforos et al. [104] proposed generation scheduling of the hydro production system as a mixed-integer, nonlinear optimization problem and solved with an enhanced genetic algorithm featuring a set of problem-specific genetic operators. The thermal sub problem is solved by means of a priority list method, incorporating majority of the thermal unit constraints. The approach developed is applied to Greek power system with 13 hydro plants and 28 thermal plants. The HTC problem is decomposed into hydro and thermal and hydro sub problem is solved by heuristic decomposition methods. The thermal optimisation sub problem is then attempted using thermal cost functions or thermal system marginal cost to efficiently allocate water resources within the scheduling horizon. The authors have formulated the hydro sub problem as a non-linear mixed integer optimisation problem. The modelling includes operating limits, head dependent efficiencies and discrete pumping operation. The annual variation in inflow and storage management is not considered in this approach. The approach is fine, but what it lacks is the capability of the power system to absorb market power to increase the storage in the hydro reservoirs for maximisation of profit during lean monsoon periods. The paper is based on the conditions of Greek, which is entirely different from a tropical control area like Kerala.

Andres et al. [105] models the medium-term operation of the system to compute system marginal cost and refinement of hydro scheduling algorithm. The authors assume Cournot conjecture in electricity market, that is, the firms compete only in quantities, while the price is derived from the demand function. The objective of the generators participating in the model is maximisation of profit. The generators' surplus for a certain load is computed as the difference between revenues and costs. The proposed algorithm obtains and initial equilibrium with high system marginal price for a particular load level. Another load level with lower system marginal price is then identified where the same company can reduce generation. The hydro generation is then exchanged with this fringe strategic company (considering the constraints of hydro). The medium-term operation planning is done in this approach also, but instead of assuming the hydro generation potential, we intend to go to determination of hydro generation potential itself.

Farhat et al. [106] gives a literature survey of literature on the various optimization methods applied to solve the Short-term hydrothermal coordination (STHTC) problem. Deterministic methods, including Lagrangian relaxation, Benders decomposition methods, mixed integer programming, dynamic programming and interior point methods, are often used in short term hydro thermal coordination. Heuristic methods like genetic algorithm, particle swam optimisation, and other evolutionary methods are finding application in solving large scale optimisation problems. The heuristic techniques use stochastic techniques and include randomness in moving from one solution to the next thus avoiding local minima, while deterministic methods follow deterministic transitions rules.

Mario et al. [107] presents methodologies and tools being developed to address the new challenges and opportunities posed by power sector restructuring in hydrothermal systems such as optimal stochastic dispatch of multiple reservoir systems, joint representation of equipment outage and inflow uncertainty, distortion of short-run marginal costs signals when applied to cascaded plants with different owners and economic efficiency & market power issues in bid-based hydrothermal dispatch with reference to Columbian system. The thermal generation dispatch problem is decoupled in time as the generation in one unit does not affect the generation at a different time period. With the introduction of hydro, this gets coupled. The immediate cost function and future cost function are evaluated and the optimal hydro dispatch is at the point at which these costs become equal. The method proposed in our work is further elaborative in the sense that the thermal part is separated from the principles of peak shaving and the hydro optimisation is carried to the extent that the reservoir level is always maintained high considering the probable highest rate of inflow and the maximum possible rate of discharge through the generators. Hence the method developed in this thesis is expected to give better results.

Thomas et al. [108] describe the Dynamic Unit Commitment and Loading (DUCL) developed for use in real-time system operations at British Columbia Hydro (BCH) to determine the optimal hydroelectric unit generation schedules for plants with multiple units and complex hydraulic configurations. The model system has 30 hydroelectric plants with 31 reservoirs (6 major basins and 25 watersheds). Thermal generation through purchase contribute only 5% of the total energy consumption. In this paper also, the maximum generation capability is taken as a function of head, which is a real-time function and not included as a planning figure. The availability of water is not cited as a constraint on seasonal basis. As such, this method cannot be applied for hydro thermal scheduling in tropical countries. The hydro thermal mix in our case in Kerala is almost the opposite of the British Columbia system, with almost 75% thermal import and 25% hydro during normal monsoon year.

Bensalem et al. [109] compares the management strategies followed for hydroelectric power plants for short term optimal operation. First strategy is maximization of reservoir contents at the end of the exploitation period and the second strategy is maximisation of reservoir contents at the end of sub periods of the same exploiting horizon. In order to solve, a new objective function, represented in the water potential energy, which permits to minimise the use of water is proposed. The system considered is a hydropower system with ten hydraulically coupled reservoirs, in the same river. Natural inflows are also considered. The scheduling is stretched over one week. Though natural inflow is considered, the variation that could happen is not considered in this analysis. Further, the application is limited to one hydropower system only. Thus, this paper also discusses the optimization from the view point of a generator. We have considered decoupled hydro systems in our work. Further, the optimisation within the hydraulically coupled schemes is proposed to be left to local optimum, and the output of such schemes is worked out in the global optimum solution. We are accepting the basic principle of maximizing water content at the end of sub periods and additionally, we are estimating the spill threat to decide on the quantity of electricity to be generated in each sub period. In merit order scheduling, the generation from a station under spill threat is based on its cost of generation, but if there is no spill threat, the merit order has to consider a higher rate, which will be, theoretically, the cost of energy that it could replace.

Brovold et al. [29] proposes a method for implementing enhanced hydropower planning formulation in a long-term expansion planning model. This involves assigning hydro generation a marginal cost through water values. The study is to provide a long-term plan for timing, size and location of generation capacity and inter-country transmission system at minimum cost in Europe for the period from

2010 to 2060, considering the renewable integration. In the modelling, each country is denoted as a n node system, and each year is modelled as 10 consecutive seasons. The hydro schemes are modelled separately as regulated and run-of-the–river. Water value is defined as future expected value of stored marginal kWh, which ensures that water is not depleted first. In the start of each season, initial reservoir level is set and inflow is assumed to take place immediately in the beginning of each season. For simplification, the seasons are categorised into summer and winter, and for the base scenario, 80% and 60% were assumed as the initial storage during each season. Other scenarios studied are 90% - 70% and 70% - 50%. However, these conditions cannot be taken in Indian conditions. In the peninsular India, in particular, the Monsoon is the source of water to the reservoirs. The optimisation being on the overall cost of energy procurement for distribution for the control period, the requirement of non-Monsoon period is to be treated carefully. Also, the spatial distribution of rain during monsoon period is not uniform as in temperate zones, hence the storage optimisation as per this method results in sub optimal utilisation. We have covered these issues in our model and approach.

Zhai et al. [56] discusses a quadratic program model for optimal scheduling of hydro generation and also the unit commitment among hydro generating units. Here, the authors have proposed the variations in demand to be absorbed by the coal-based generators alone. The case has been taken from China, where 70% or the total power is sourced by coal based generating stations. The nuclear sources are considered as base generation with no variation at all. This is also possible only if the nuclear contribution in the overall system is very small. Two models are then created. Model 1 solves the allocation of hydro loads and thermal loads. The second model solves the problem off optimal power dispatch. In the proposed schemes, the control period wise optimization is not attempted. Further, there is no attempt to put a value for water, without which the water in the storage reservoirs will get depleted first. The market component is not at all considered. We have taken all these aspects in our work.

The development of a model to suit the Indian condition necessarily has to consider the Indian Electricity Grid code and Kerala State Electricity Grid code [110]. For storage optimization, the assessment of inflow to the reservoirs during various time periods is very sensitive information.

The impact of weather forecast in power system is multi-pronged. The major effects of wet weather continuing for a couple of days are (i) inflow to the reservoirs increase (ii) rate of inflow changes almost in direct proportion to the precipitation if the rain continues for three- four days, (iii) demand may fall (applicable in tropical countries more abruptly) (iv) changes in the renewable generation (including hydro without storage) etc. Thus, more or less accurate weather forecast is a requirement for system manager. Decadal to inter-decadal variability in atmospheric conditions is observed by the meteorologists. Among the observations, Pacific Decadal Oscillations (PDO) and Atlantic multi decadal oscillations (AMO) are associated with historical extremes in weather [111]. The multi decadal and decadal observations are tools to decide on the progress of construction of new power plants and transmission system. Indian Meteorology department (IMD) [112] is the official agency in India to provide climate and weather related information.

There has been stress on the increased contribution from the renewable sources in view of the perceived global warming effects. Several countries, including India, are signatories of the Kyoto Protocol [113], which aims at reducing the rate of increase of emission of the greenhouse gases. Power generation sector is one of the most contributing sectors emitting greenhouse gases. Increase in the penetration of the renewable energy sources in the power procurement portfolio has serious impact on the optimum generation from various sources. The impact is to be absorbed more by the hydro generating units, which have the least start-up / shut down cost as well as time. Thus, the requirement of storage optimisation is gaining more significance now.

2.9 GIST OF OBSERVATIONS

The optimisation studies done in power system operation is umpteen and some of them have been commercially put into use. The electricity industry has been implementing the research solutions right from the early days. The optimisation of operation for minimising the price of energy distributed in a control area, is however not seen attempted much.

Most of the methods had the issue of non-portability and limitations in the parameters considered, associated with the structure of electricity industry in different countries. For instance, the balancing market in European system, Locational Marginal Pricing adopted in US, Availability Based Tariff (ABT) mechanism adopted in India etc. are distinct and any optimisation study has to be tuned to the industry structure.

Any optimisation program normally starts with a SWOC analysis, earlier referred to as SWOT analysis. SWOT analysis as applied to a control area concept could not be found. Almost all papers were about the analysis of generator, group of generators or of distribution licensees. When internal generation and market operation for distribution are considered holistically, the internal generators are to be evaluated in the same platform as that of competing generators. The SWOC of the control areas differ from one another. We have carried out the SWOC analysis of Kerala control area and also developed the general methods by which the SWOC of any control area can be analysed.

The basic requirement of the optimisation work is the assessment of the requirement. The area of load forecasting is pretty well attempted and several commercial solutions are also available based on several statistical and numerical methods. Most of the methods take calendar information, weather information etc. But on review in some of the utilities operating such software in India, it was seen that all data as required by the software were not readily available for the training data and even now. Similarly, it was observed that though the packages had provision for weather parameters in detail, there were no provision for classifying the holidays as national holidays, religious holidays etc, which is found to have high impact on the demand pattern. Some of the papers have suggested automated selection of similar day, but this method when tried with one of leading forecast package gave monthly average MAPE of more than 7%. The same package when tried with normal working days gave monthly average MAPE less than 2%.[3]

The behaviour of various methods is drastically different as the forecast horizon is expanded. The methods for medium term and long-term forecasts also need to consider the extraneous factors such as government policies. Another factor which is not captured in the models studied was the absence of operational efficiency achieved in the electricity applications at user side on account of technology changes

[3] The performance of the commercial packages of a few (three) distribution utilities in India other than Kerala was studied, but the details cannot be published on account of secrecy of the data and analysis of results.

such as LED lighting, high efficiency motors, higher renewable penetration etc. The methods used such as econometric models, statistical models, end use approach, multiple regression using GDP, and combination of these etc. were found to have tendency for over estimation.

The over estimation of requirement results in increase of fixed component in the price of energy delivered in the control area. However, the requirement of energy over a few years was found to be good enough in several methods, the major difference was in the peak power demand. But, a realistic forecast of peak power requirement is also essential for finalising the power procurement strategy of the distribution licensee as the power procurement cost is the major cost component in the price of energy delivered in the control area.

From the various methods in use, we decided to go for the energy forecast with available best method suited for the control area. The solution to the determination of peak power requirement was achieved by using a combination of load profiling technique reported for short term studies and energy forecast by standard tools. The results were good for the last 7-8 years for Kerala control area.

2.10 CONCLUSION

The various aspects of power system study that is being undertaken at various parts of the world are summarized above. From the very fact that a topic of techno-commercial interest has created so much interest in the research world points out to the importance of the topic. It was seen that most of the papers referred are approaching the solution through mathematical models with computations which involve several numerical methods. While the numerical methods give good results with test data, the complications that arise in the operation on real time are not captured in most of the papers. Such complications include, but not limited to, political events, sudden changes in weather, sudden surge in demand, unanticipated shortages in fuel availability, shortage or non-availability of rail rakes or issues in rail transportation etc. These are captured in short horizon and the optimisation package has to be re-run for solution. This requirement necessitates a method to be operated by the novice operation mangers, without much expertise in modelling. Some of the constraints developed may not be fully amenable for mathematical modelling directly. Through this thesis, we are bridging this gap.

CHAPTER 3

DEVELOPEMENT OF RESEARCH FRAMEWORK

3.1 INTRODUCTION

The optimisation studies done in power system operation are umpteen and some of them have been commercially put into use in different countries. The electricity industry has been welcoming the research solutions for implementation right from the early days. The optimisation of operation for minimising the cost of energy distributed in a control area is however not seen attempted much, more studies have been on the cost optimisation or profit maximisation of generation. Only few papers could be traced in this area and most of them had the issue of non-portability and limitations in the parameters considered.

3.2 LIMITATIONS OF THE EXISTING APPROACHES

This is a real world problem. All parameters and constraints which are likely to have impact on the cost of energy procured for delivery in a control area to be considered. Such a comprehensive solution approach could not be traced though parts of the problem are attempted in several researches. The reviewed papers were having serious limitations of non-portability on account of the rigid formulations adopted based on the system studied.

Major limitations of the existing approaches are summarised below:

- Parts of the problem are seen attempted by several researchers. Most of such papers were having serious limitations of non-portability on account of the rigid formulations adopted based on the system studied.
- Most common issue observed in pure academic works is that the parameters considered are limited on the basis of availability of data. The practical issues like the cost involved in updating the data, the sensitivity of a particular data

in the overall recommendations derived from the study etc. are often seen ignored.

- In some cases, parameters are overly considered, without recognising the availability in real world. For example, the availability of weather data for different parts of the control area for last 15 years seen modelled in a paper, with the disclaimer that the test data is taken only for four locations.

- The sensitivity of data considered for statistical reasoning is not seen properly addressed. There cannot be any approximation in any parameter or constraint for obtaining convergence in real world problems.

- The marginal benefit on account of introducing a parameter and the loss of accuracy by ignoring that has to be evaluated are not seen addressed in several approaches. This is important as the result is to be used by a commercial entity.

- In most of the approaches, hydro generation is reserved for peak shaving. This approach is generally based on the inherent advantages of hydro generation with respect to the controllability in terms of quantity (generation output) and the speed of achieving the change in the generation. However, the market forces are not considered and schedulable hydro to replace with market component not seen attempted.

- Refinement of the hydro shaving method attempted in some cases are based on heuristic decision making and supported by rule curves for storage reservoirs, derived from mere past observations and not supported by detailed calculations and hence cannot be said to be optimum on its own.

- Convergence issues in Hydro –Thermal Coordination (HTC) problems is found to solved by reduction in the duration of control period so that the issue of availability of water in the reservoirs is taken care of. However, this results in sub optimum hydro generation when considered on annual basis. The optimisation of the hydro generation is not seen attempted on annual basis in any of the papers.

- The power system management of Kerala and Assam, on account of the steep ramping of demand during evening peak and the availability of hydro generation with pondage and storage type in abundance, has been considered satisfactory, but when reviewed critically with all options available, it was found that the operation was not optimum in the past.

- The basic requirement of the optimisation work is the assessment of the demand for electricity. The area of load forecasting is pretty well attempted and several commercial solutions are also available. Most of these are based on several statistical and numerical methods. A few papers are also noted with the technique called load profiling. In most of the methods, provision is seen made for calendar information, weather information etc. But on review of the experiences shared by some of the utilities operating such software in India, weather data as required by the software for training are not readily available for updation and the data taken as representative of the control area sometimes does not reflect the average conditions. Taking multiple weather station data and subdividing the control area for granular forecasts are also seen attempted, but the results in some cases are found to deviate significantly[4]. This was causing severe errors especially when the weather is changing. Similarly, it was observed that the demand forecast on holidays, especially religious and national holidays resulted in more error than normal working days. Some of the papers have suggested automated selection of similar day, but this method when tried with one of leading forecast package gave monthly average MAPE of more than 7%. The same package when tried with selected similar day data (in sufficient number) gave monthly average MAPE less than 2%. [5]

- The behaviour of various forecast methods is drastically different as the forecast horizon is expanded. One of the basic observations from the experiences shared across the world, including those of Indian states was that the methods for medium term and long-term forecasts also need to forecast the government policies. Even for developed countries where the electricity consumption is stagnant for last several years, the operational efficiency achieved in the electricity applications at user side actually contribute partly to the present situation of zero growth.

- The methods used including econometric models, statistical models, end use approach, multiple regression using GDP, and combination of these has a general tendency of over estimation. The over estimation of energy requirement, results in increase of fixed component in the price of energy delivered in the control area in terms of capacity addition in Generation and Transmission sectors in particular.

- Market based operation optimisation is seen attempted in the research world in different ways. However, the basic presumption is built from the availability of power from different sources, in which hydro is also assumed. This assumption is not seen attempted simultaneously.

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4 As these observations are prone to statutory audits and being commercially significant, the exact source of the data is covered in official secrecy and data sharing agreements.

5 The large error had affected the optimum operation of such control area on such dates. Details are however, classified.

3.3 METHODS DEVELOPED

The proposed solution is achieved in six steps. These are:

Step1: Identification of the limitations of the existing methods and the methods developed in various research papers available.

Step2: Obtain long term demand forecast using any standard method. Develop simple and consistent method for deriving the peak and off peak demand and the energy requirement.

Step3: Develop method for SWOC analysis of the power system under consideration with the objective of reducing the cost of power procurement and for determination of schedulable and must-run generation in time domain

Step4: Determination of price for the schedulable generation component including hydro generation from various generating stations considering the reservoir parameters and inflow pattern

Step5: Determination of power procurement portfolio based on steps 2, 3 and 4 and check for optimality by applying on historical data for verification of the results obtained with respect to the optimum solution.

Step6: Compare the cost impact with respect to the operation of the grid using methods developed.

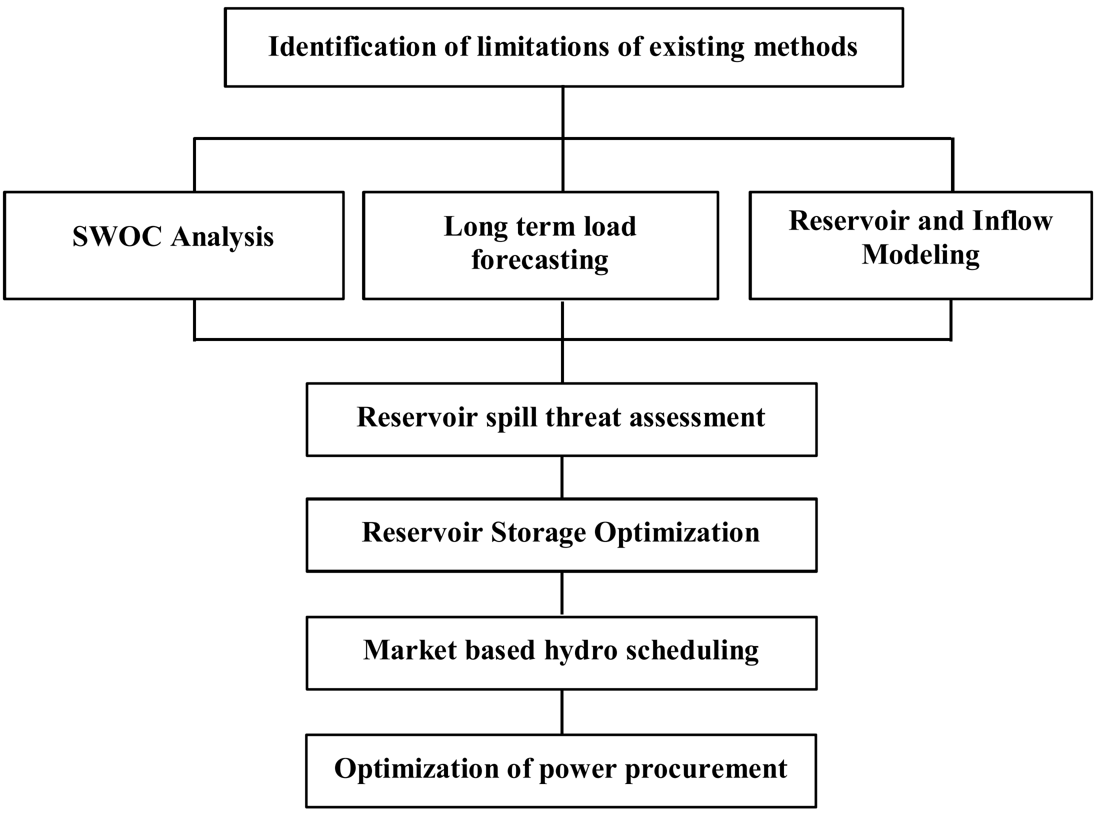

Fig. 3.1 Research Framework

3.4 MATHEMATICAL MODELLING

Mathematically, the research problem can be summarised as follows:

Objective function

Minimise the cost of power procurement P_E for the control area for the control period

Mathematical Model

P_E = Price of energy procured for the control area for the control period

From fundamentals,

$$\text{Price} = \frac{\text{Cost} + \text{Overheads including returns}}{\text{Units sold}}$$

Here, to simplify the steps involved, the transmission & distribution charges, losses, overheads, operational expenditure and the return on equity of the utility as per the rules and regulations are also apportioned to the source of power and price of each source is taken. This is a common industry practise.

Hence, P_E is given by

$$P_E = \frac{P_B E_B + P_P E_P + P_{BAL} E_{BAL}}{E_B + E_P + E_{BAL}} \quad (3.1)$$

P_B = Price of power contracted as base power

P_P = Price of power contracted as peak power

P_{BAL} = Price of balancing power

E_B = Energy procured as base energy for the control period

E_P = Energy procured as peak energy for the control period

E_{BAL} = Energy procured as balancing energy for the control period

E_{BAL} is the difference between the energy procured/ contracted € and the actual energy requirement for sale in the control area. This can be positive or negative

Power requirement MW_n is practically uniform for a specific duration, subject to change in the exact timings month over month. Day can be divided in general to 5 time blocks as given below with the average power requirement as shown.

MW_1 =Night off-peak- from 00:00 hrs to 05:30 hrs and 23:00 hrs to 24:00 hrs

MW_2 =Morning peak – from 05:30 hrs to 07:30 hrs

MW_3 =Day time – from 07:30 to 18:30 hrs

MW_4 =Evening peak – from 18:30 to 23:00 hrs

Then the Energy requirement, from basic principles, can be expressed as

$$E = 6.5\ MW_1 + 2\ MW_2 + 11\ MW_3 + 4.5\ MW_4 \quad (3.2)$$

If λ is taken as the average annual load factor and P as the annual average peak demand, from the fundamental equation for the load factor, we can deduce that

$$E = \text{P}.\lambda.\ (24x\ 365)$$

$$= \text{P}.\ \lambda.\ 8760\ \text{MWhr-} \quad (3.3)$$

Constraints:

1. The total energy requirement E is to be balanced from all available sources on merit order for ensuring minimisation of P_E
2. The power balance equation is to be satisfied in real time. Mathematically,

$$MW_n = MW_{coal} + MW_{hydro} + MW_{Ren} + MW_{Others} + MW_{Bal} \quad (3.4)$$

where,

MW_n = Real time power requirement in time slot n
MW_{coal} = Power scheduled from coal based stations in time slot n
MW_{hydro} = Power scheduled from hydro stations in time slot n
MW_{Ren} = Power scheduled from Renewable stations in time slot n
MW_{others} = Power scheduled from all other sources in time slot n
MW_{Bal} = Power scheduled as balancing power in time slot n

3. If E_{BAL} is negative, there is surplus energy content available and has to be sold to the market. However, this is limited to the period when there is power surplus also. As the hydro availability is not uniform and depends on the monsoon, the power availability balance will be different for different sub periods

4. The base energy procurement E_B is determined by the linearization of the annualised load curve as derived in this thesis.

5. The peak energy is based on the peak power requirement determined from the annual energy requirement as per the method derived in this thesis.

6. The availability from each source is to be worked out considering the peculiarities of each source and the techno-commercial constraints in scheduling.
7. There is no distinction between the energy generated from internalised generating stations of the distribution licensee and the procurement from other sources including the different markets.
8. Balancing power is not restricted to purchase from markets, but also include the margin available in the internalised generation including hydro, determined by merit order scheduling.

3.5 STEPS IN RESEARCH SOLUTION

- Study of the Strengths, Weaknesses, Opportunity and Challenges (SWOC) of the power system bounded in the control area with respect to the operational issues and the factors influencing cost of power delivered in the control area.
- Determination of base power requirement and peak power requirement on longer time horizons with sufficient accuracy. This is required for finalising the suitable contracts for base power and peak power on longer horizons. The strategy for market operation in short-term and long-term is different and has to be coordinated for optimum results.
- Optimisation of hydro generation based on the schedulable and must-run hydro components by fixing the must-run hydro generation considering the variability attached and fixing a price for the hydro generation for using the concept of must run and schedulable and to fit the schedulable hydro generation into the normal merit order scheduling which is done on real time.
- Optimisation of storage management in the reservoirs for ensuring maximum generation potential towards the end of active rainy period and to optimise the cost of power procurement for the control period.
- Optimisation of power procurement/ sale strategy for optimisation of cost considering the real time constraints.

These are briefly explained below

3.5.1 SWOC Analysis

SWOC analysis, earlier referred to as SWOT analysis as discussed by Albert Humphrey of Stanford University as early as in 1960s is the primary step to identify the corrective actions required. Comprehensive SWOC analysis as applied to a control area concept for management of electricity could not be found in the literature survey. Almost all papers were about the analysis of generator, group of generators or of distribution licensees. When internal generation and market operation for distribution are considered holistically, the internal generators are to be evaluated in the same platform as that of competing generators. The SWOC of the control areas differ from one another. The parameters to be considered for SWOC analysis for application on the optimisation of cost of energy procured for distribution in a control area are to be identified. The method is to be applied to practical case study for establishing the relevance and correctness of approach.

3.5.2 Load forecasting

On review of the available forecasting methods, it was found that the forecast of requirement of energy over a few years was found to be good enough in several methods, whereas the accuracy of forecast of peak power demand, which is the basis for contracting power sources, is insufficient. Realistic forecast of peak power requirement is also essential for finalising the power procurement strategy of the distribution licensee as the power procurement cost is the major cost component in the price of energy delivered in the control area. The solution to the determination of peak power requirement on long term is achieved by a combination of load profiling technique reported for short term studies and any long-term energy forecast tools.

3.5.3 Hydro scheduling

The existing method of cost determination as primary and secondary energy for hydro does not give any indication on the optimum scheduling. By determining the schedulable and must-run component in the hydro generation from each plant, the schedulable portion directly finds application in any standard merit order dispatch schemes with annual window in consideration. The method should eliminate most of the ambiguity issues in hydro – thermal coordination. Once the schedulable hydro is segregated, the price determination is done. Scheduling of hydro generation on market based optimisation requires determination of safe reservoir levels and optimum storage management.

3.5.4 Reservoir Storage Optimisation

The statistical analysis of the inflow to the reservoir and the computation of rate of inflow and depletion are used for computing a safe reservoir level for each reservoir on any day during the control period. The computation method remains the same and universal, but the analysis and conclusions are reservoir specific.

3.5.5 Optimisation of cost of energy procurement

The energy procurement through the following sources is to be considered for optimisation. These are universal in nature and common for any distribution utility.

a) Long-term contracts from conventional sources other than hydro
b) Renewable generation and generation from atomic stations (must run)
c) Hydro generation (must-run)
d) Hydro generation (schedulable)
e) Short term purchases

Among these, the price of schedulable hydro is fixed as the cost of the marginal component in the merit order stack for the entire year to balance the demand and availability. Hence, based on the actual load conditions and market conditions, the scheduling of hydro, short-term purchases and long-term purchases may overlap. This is optimised by optimising the price of power for the control period as a whole.

3.6 CONCLUSION

The research problem is explained in detail, with the mathematical modelling and the identification of constraints. The steps involved in the solution to the problem are also identified. Similar approach could not be seen in the literature survey in this holistic approach of minimising the cost of energy supplied within the control area, delinking from the profit maximisation of individual utilities and agencies.

CHAPTER 4

CONTROL AREA SWOC ANALYSIS

4.1 INTRODUCTION

SWOT analysis developed by Albert Humphrey of Stanford Research Institute in the 1960s is a common tool used in strategic planning sessions. SWOT analysis is one of the powerful tools to identify where the optimisation studies can be targeted. SWOT is a structured planning method used to evaluate the Strengths, Weaknesses, Opportunities and Threats in a project or in a business venture. SWOT analysis is sensitive to time. The strength at one point of time can become a weakness in future or vice versa. The period to be considered for optimisation studies is therefore important in identifying the elements of SWOT analysis. In view of the negativity in the term Threat, which originated from a military usage, more positive attitude is created by using Challenges. Thus, SWOC and SWOT are essentially the same, the former being able to create an energetic mind-set.

Two factors contribute to Strengths: ability and resources available. In general, "ability" is evaluated on versatility, growth and markets. The "resources" has three dimensions: availability, quality and allocation. Weaknesses in this context are assessed through losses and inability to match with dynamic situations and rapid changes (load shedding and power cut). Analysis of weakness is to adopt prevention strategies to reduce the exposure to actual weakness. Opportunities and Challenges (Threats) are external agents which are to be identified for success.

In power system optimisation studies, the major point to be noted is the gestation period for completion of a project and its average useful life. In the case of thermal generating stations, the typical gestation period is 7 – 8 years from conceptualisation to commissioning. For hydro stations, this could take one more year. However, for small run-of-the hydro stations, the gestation period could be low. For wind and solar, it could be in the order to 10-24 months. Transmission system may require typically 3-4 years for completion if there are no litigation on the right – of – way. The average life of a regulation is 5-7 years, though a number of amendments would be issued during this period. There are frequent changes in legislation also. Hence, there could be major difference in the policies and rules by the time a project is commissioned from the date of conceptualisation. The typical life time of generation and transmission assets is 30-35 years. Thus, there could be several changes in policies and regulations during the life time of a project. Hence, the sensitivity of time factor is even more significant for power system management studies.

In this work, we have successfully applied the SWOC analysis for enabling the optimization studies here. The application of SWOC analysis for optimum power system operation is developed with the case study of Kerala power system.

4.2 SWOC ANALYSIS OF POWER SYSTEM CONTROL AREA

Power system operation is structured with the concept of control area as detailed in chapter 1. In India, the control area merges with the geographical boundaries of states in most of the cases due to administrative and political reasons. SWOC Analysis of a power system essentially comprises of the assessment of strengths and weaknesses of the power system within the control area.

The objective of operating the power system efficiently include most economic operation of the grid without losing any of the renewable resources, maximum utilisation of assets and above all, maintaining reliability of power supply by maintaining sufficient margin of system security and operating within the stability margins. The objectives being multitude, evaluation opportunities and challenges are important for scientific monitoring and to take corrective action at the right time.

The economy of operation depends on several factors and can be broadly classified as internal and external. The policy changes that could affect are not only on the policies with respect to electricity, but also on the policies on transportation, mining, water, import-export, taxes etc. The SWOC analysis is done with respect to the major universal factors pertaining to the control area based management.

For a power system, on control area basis, the following are considered for SWOC analysis

- Generation mix – utility owned and acquired through contracts. This is for considering the cost of transmission system.
- Hydro thermal mix is one of the major parameters. The content of each of the renewable – viz. hydro, solar and wind – is having direct correlation with availability, variability and cost.
- For thermal units, the main operational criteria are start-up time and start/ stop cost. Unit size and variability of generation are the other factors usually appearing in SWOC analysis.
- Locational advantage of thermal stations is another major consideration. As a general rule, transportation of fuel for generating electricity over long distance is costlier than transportation of energy in the form of electricity from the same location, which is strength for pit head stations. Similarly, there is no logic in constructing a 100% indigenous-coal based plant in a coastal area where imported coal and indigenous coal may effectively cost the same.
- Unit size of the generator is another important parameter. The technology and the unit rating decide the minimum generation at which the generator can be operated without appreciable additional expenditure. This aspect is significant in the background of increasing renewable power penetration.
- Nuclear stations, solar PV, wind and small hydro are normally classified as must – run generation. While the thermal generation based on coal have a

techno-economic minimum threshold generation of around 50%, the hydro plants can be started and stopped with minimum delay and in minimum cost. Gas based open cycle projects also have the flexibility of start – stop operation.

- If the load reduces below the simultaneous minimum of such sources and the techno-economic minimum of coal based stations, there could be significant revenue loss for the distribution company.

4.3 LOAD CURVE

The load curve basically indicates the utilisation of the assets created for power system management. The various parameters derived from the load curve directly find application in strategic decisions. A demand load curve in line with the generation load curve indicates maximum utilisation of the assets created for distributing power within the control area. The longer the duration of peak, the more is the utilisation of the base load generation assets and transmission assets. Typically, load factor, peak load, load duration, minimum load, minimum to maximum load ratio etc. figure out in the SWOC analysis. The load curve has a direct bearing on the optimality of generation mix. As there exists a cross relation between these two, the relations are not simple.

4.4 CONSUMER PROFILE

Consumer profiling is important in tariff finalisation. Consumer profile is a major factor that indicate the consumer behaviour in consumption. A high base load is always indicating industrial consumption. Domestic and commercial loads show peaking characteristics and are coincident to some extent, though there could be some difference in the time of utilisation. The information of the consumer profile is necessary to forecast the demand on short term basis, where the impact of weather, nature of the day – working day, holiday, hartal etc. is significant.

The geographical peculiarities of the control area is another major component of the SWOC analysis. Development of cheaper generation within the control area itself or construction of transmission system for inter control area power transfer is essential for meeting the control area demand. The availability of right of way for transmission system is a critical parameter in timely commissioning of transmission system and also completing the project with no cost overrun. In SWOC analysis, these two aspects are to be considered simultaneously. In other words, the possibility of development of generation facility is always "strength" for the control area, while the converse is not always a weakness, especially if the internal generation is costly and augmented transmission system can be put in place.

A practical case of SWOC analysis is done with Kerala power system as a case study. Kerala power system has the typical characteristic of high dependency on inter-state transmission network, predominant internal hydro generation, sharp evening peak etc. which are not seen discussed in papers published on SWOC analysis.

4.5 UNIQUENESS OF KERALA CONTROL AREA

Kerala state has several unique attributes. Much of them are traced to have roots in the geographical disposition of the state, wedged between Western Ghats on the east and Arabian Sea on the west with some 150-odd km width at the widest point. The eastern part of the state is guarded by Western Ghats, with thick forest cover, isolating the state form the neighbouring states in some aspects. Though the state is blessed with several rivers ideal for construction of good hydroelectric projects, the environmental fragility of the Western Ghats is a major impediment. The state is directly exposed to south west monsoon and also receives fairly good rainfall from north east monsoon. The south – west monsoon is followed immediately by north – east monsoon. Both these cover about five months of active rainfall. The long period of rainy days facilitates rich fauna and flora all through the state. The thick vegetation and high density of population are characteristics of the state. The state is also having forest coverage above the national average. As per 2015 assessment, the total forest area in Kerala is about 49.50% of the total area. If the ten hill districts alone are taken, the forest cover is 52% of the total area. This is against the national coverage of 21.34%. The high forest area has further increased the population density. The population density of Kerala as per 2011 census is 860 persons per sq. km compared to the All India average of 382 persons/ sq. km. The high density of population and high forest cover is causing many hurdles in construction of new power houses and also new transmission lines.

Kerala power system has inherited several unique characteristics from the uniqueness of the state. Typical of them are the electricity usage pattern, growth pattern in the consumption of electricity, construction of transmission system and generation stations, outages on account of faults etc. The unique characteristics associated with the consumption pattern of electricity and the development of infrastructure is studied here, which are relevant to the optimum operation of the power grid.

4.6 HISTORY OF POWER SECTOR IN KERALA

The history of power sector in Kerala can be traced for more than a century. Dr. D.Shina [83] has given a concise history of the Kerala Power system. First installation was a hydroelectric project near Munnar in 1910 by the Kannan Devan Hill Produce Company, mostly for own use, with no commercial significance. Subsequently by 1927, thermal stations were set up in Thiruvananthapuram by the king of Travancore and subsequently at commercial centres at Nagercoil, Kollam and Kottayam by 1934. These were managed by the electrical wing of the Public Works Department of the government. The development is seen in line with the developments in other parts of the country. The oil sets were essentially operated in islanded mode with a few consumers connected.

First major hydroelectric project in Kerala came up at Pallivasal by 1940 with a diverting weir at Munnar, one of the major hill stations in South India. The initial capacity was 13.5MW with 3 units of 4.5MW each, which was subsequently upgraded to 5MW units by replacing the runner. Another set of 7.5MW units were added subsequently, making the installed capacity 37.5MW, but limited to 32MW on account of penstock capacity. The power evacuation was at 66kV level with substations at Kothamangalam, Aluva, Kottayam, Mavelikkara and Thiruvananthapuram. A reservoir at Kundala in 1947 with a storage of 7.787MCM, and by 1954 another reservoir with a storage of 55.4MCM, which also has the distinction of first all concrete dam in India, were commissioned so that the generation potential of the station could be fully utilised. Subsequently the grid was expanded and other generating stations commissioned. It is seen that the significance of hydroelectric schemes in providing low cost electricity was properly conceived and the investigation for several hydroelectric projects started by this time. Thus, the history of power sector in Kerala saw both emergence and exit of private generators. The formation of Kerala State Electricity Board in 1957 in accordance with Electricity (Supply) Act 1948 resulted in accelerated development in the electricity generation and supply within Kerala. At the time of its inception as KSEB the installed capacity was 109.5MW. The major keystones in the development of Kerala power system are tabulated in Table 4.1.

Table 4.1 Growth of Installed capacity in Kerala control Area

Station		Installed capacity (MW)	Year of commissioning	Renovation	Renovated capacity (MW)
Pallivasal	Unit1	5	1940	2001	5
Pallivasal	Unit2	5	1941	2001	5
Pallivasal	Unit3	5	1942	2001	5
Pallivasal	Unit4	7.95	1948	2002	7.95
Pallivasal	Unit5	7.95	1949	2002	7.95
Pallivasal	Unit6	7.95	1951	2002	7.95
Sengulam	Unit1	12	1954	2002	12
Sengulam	Unit2	12	1954	2002	12
Sengulam	Unit3	12	1954	2001	12
Sengulam	Unit4	12	1955	2001	12
Poringal	Unit1	8	1957	2014	9
Poringal	Unit2	8	1958	2014	9
Poringal	Unit3	8	1959	2015	9
Poringal	Unit4	8	1960	2015	9
Neriamangalam	Unit1	17.5	1961	2004	17.5
Neriamangalam	Unit2	17.5	1961	2005	17.5
Neriamangalam	Unit3	17.5	1963	2006	17.5
Panniar	Unit1	15	1963	2003	16.2
Panniar	Unit2	15	1964	2003	16.2
Sabarigiri	Unit1	50	1966	2009	55
Sabarigiri	Unit2	50	1966	2009	55
Sabarigiri	Unit3	50	1966	2008	55
Sabarigiri	Unit4	50	1967	2014	60
Sabarigiri	Unit5	50	1967	2006	55
Sabarigiri	Unit6	50	1967	2005	60
Sholayar	Unit1	18	1966		
Sholayar	Unit2	18	1968		
Sholayar	Unit3	18	1968		
Kuttiadi	Unit1	25	1972		
Kuttiadi	Unit2	25	1972		
Kuttiadi	Unit3	25	1972		

Kuttiadi	Unit4	50	2001		
Kuttiadi	Unit5	50	2010		
Kuttiadi	Unit6	50	2010		
Idukki	Unit1	130	1976	2018	130
Idukki	Unit2	130	1976		
Idukki	Unit3	130	1976		
Idukki	Unit4	130	1986		
Idukki	Unit5	130	1986		
Idukki	Unit6	130	1987		
Idamalayar	Unit1	37.5	1987		
Idamalayar	Unit2	37.5	1987		
Kallada	Unit1	7.5	1994		
Kallada	Unit2	7.5	1994		
Kanjikode Wind	1 to 9	2.025	1995		
Peppara	Unit1	3	1996		
BDPP*	1 to 5	105	1997		
LP	Unit1	60	1997		
LP	Unit2	60	1997		
LP	Unit3	60	1997		
Madupetty	Unit1	2	1998		
Kakkad	Unit1	25	1999		
Kakkad	Unit2	25	1999		
PLBE	Unit1	16	1999		
KDPP*	1 to 6	128	2000		
Malampuzha	1×2.5	2.5	2001		
Malankara	3×3.5	10.50	2006		
Chembukadavu I	3×0.9	2.7	2003		
Chembukadavu II	3×1.25	3.75	2003		
Urumi I	3×1.25	3.75	2004		
Urumi II	3× 0.8	2.4	2004		
Lower Meenmutty	1×0.5	0.50	2006		
Lower Meenmutty	2×1.5	3.00	2006		
NES	unit1	25	2008		

Kuttiady tail race	3×1.25	3.75	2009
Poozhithode	3×1.6	4.80	2011
Ranni-Perunadu	2×2	4.00	2012
Peechi	1×1.25	1.25	2013
Vilangad	3×2.5	7.70	2014
Adyanpara	2×1.5	3.00	2015
Adyanpara	1×0.5	0.50	2015
Amabalathara Solar	38	38	2017

During the period from 1969 to 1985, Kerala had surplus and cheap electricity compared to other states. Several power intensive industries were attracted to Kerala and the employee strength per unit of electricity was less than the national average. Deferment of Silent valley and Pooyamkutty projects in 1970s resulted in the change of status from energy surplus to energy deficit control area.

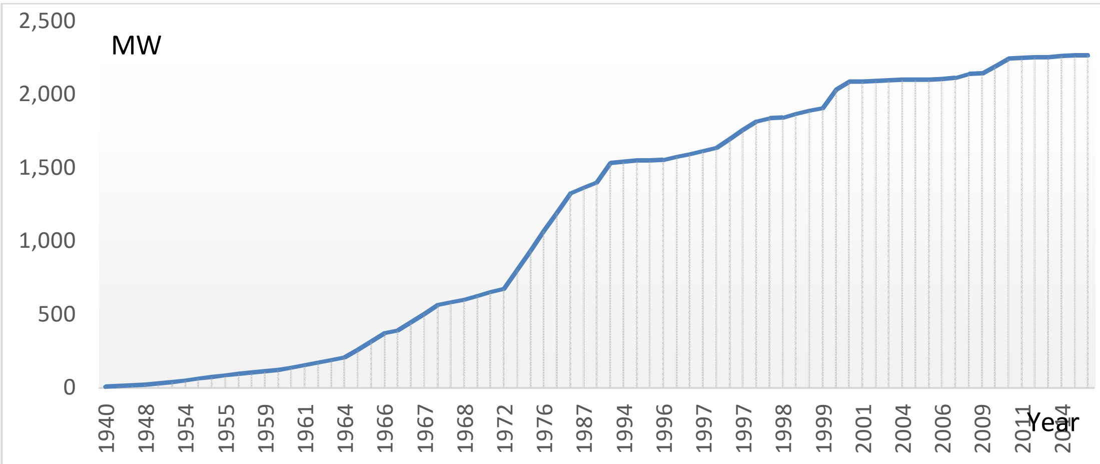

Fig. 4.1 Growth of Installed capacity in Kerala

As evident from Fig. 4.1, the growth in installed capacity has flattened by the end of 1990s. This is on account of the projected environmental fragility of the Western Ghats preventing projects of good storage capacity. The small hydel projects were considered and implemented subsequently, however, they are not financially viable as in Himalayan slopes as the water availability during summer is very limited. This account for the flattening of the curve from 2009.

Integrated operation of the power system and setting up of generating stations in central sector as regional assets was the source of power for Kerala in the subsequent years. However, the dependence on monsoon continued as hydro energy accounted for more than 50% of the total energy demand till around 2016-17 and Kerala faced severe crises during monsoon failures. The emergence of market operation in electricity by 2006 onwards was the next big change that helped the grid management in Kerala. The present structure permits a lot of optimization possibilities in the management of grid operations.

4.7 MATHEMATICAL ANALYSIS OF KERALA POWER SYSTEM

4.7.1 Load curve

Mathematically, load curve is a plot of the instantaneous demand of power in the control area, φ_t in time domain for the period from 00:00 hrs to 24:00 hrs. From the basic principles, the energy supplied for the day E is given by the time integral of the instantaneous power. Hence,

$$E = \int_0^{24} \varphi_t \; dt \tag{4.1}$$

Observations from the load curve

Following observations are made after detailed analysis of the load curve.

- The load curve of Kerala shows very sharp evening peak. The variation of φ_t is often referred to as load ramping.
- Morning peak is not insignificant, but the ramping is slow. The day time demand also reaches the morning peak level on some days [89]. The peak to off-peak demand ratio is very high for Kerala.

Elimination of spurts and exceptional cases

The analysis for determination of the salient features of the control area for concluding the power procurement strategy requires elimination of diurnal and seasonal variations in demand. This is achieved by averaging the demand of each time period on all 365 days. The average is then converted into percentage of the maximum demand to normalise with respect to the annual demand increase. The annualised average load curve for 6 years is plotted in Fig 4.2.

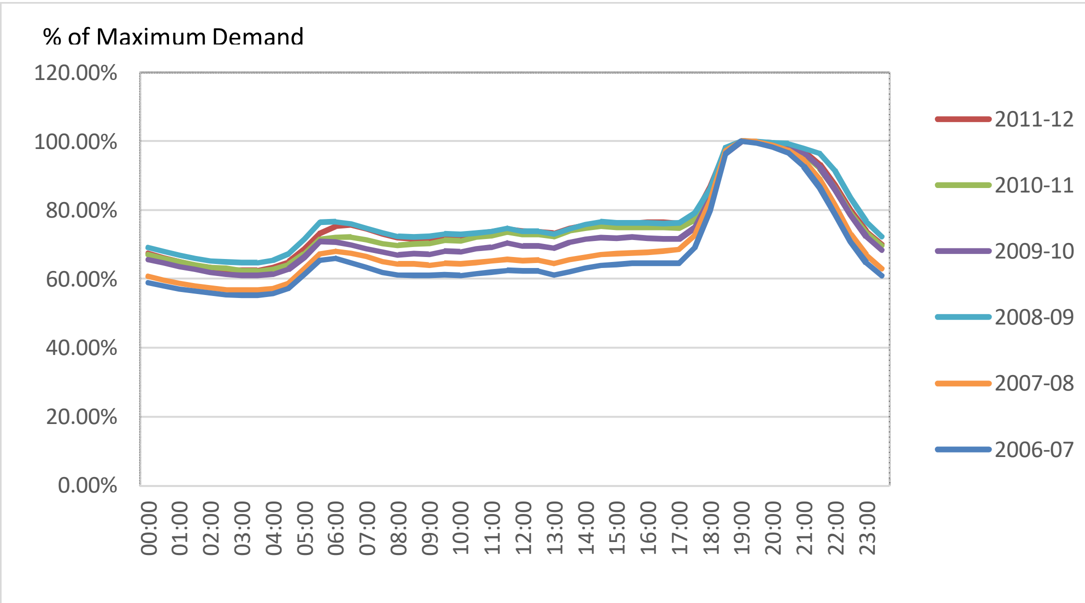

Fig. 4.2 Normalised Annual Load Curve

From Fig 4.2, it is clear that the shape of the curve essentially remains same, indicating no appreciable change in the load factor of the control area. It also indicates disproportionate commercial and domestic load compared to the base industrial load.

4.7.2 Load factor

Another prominent indicator of the control area power system is the load factor. Load factor represents the percentage utilisation of the assets of the power system. Load factor is given by

$$\lambda = \frac{\varphi_{max} \text{ x } 24}{E}$$

$$= \frac{\varphi_{max} \text{ x } 24}{\int_0^{24} \varphi_t \, dt} \qquad (4.2)$$

where, φ_{max} = Maximum (φ_t) during the period under consideration

For industrial load, the consumption may be almost uniform for the entire day. Commercial load peaks up by noon and continues to night. Domestic load picks up the evening hours and morning hours. The load factor significantly differs with the respect to the changes in the consumer base, weather conditions, location of the control area and other socio-cultural behaviour patterns. The comparison of load factor of other states in Southern Region of India is given in Fig. 4.3 [95].

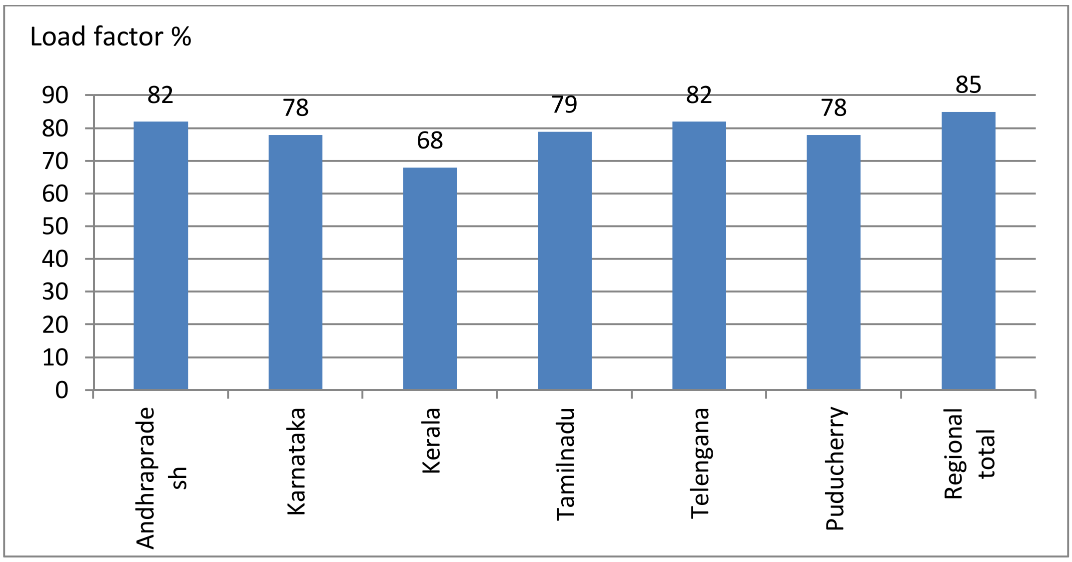

Fig. 4.3 Annual Load factor of Southern Region of India

From Fig.4.3, the load factor of Kerala power system is much lower than that of other states in Southern Region. This is contributed by the consumer profile, which has a predominant domestic and commercial consumption and low industrial consumption. 100% load factor indicates optimum utilisation of the assets underlying. At lower load factor, the assets selected shall also be suited to match with the load factor so as the full utilisation of assets is ensured for achieving the global optimisation.

4.7.3 Per Capita Consumption

Per capita consumption is defined as the consumption per individual in the control area. The per capita consumption is given by the relation

$$\text{Per capita consumption} = \frac{\text{Energy consumed for the year}}{\text{Population}} \qquad (4.3)$$

The per capita consumption of electricity consumption is increasing in almost all parts of the world except some well-developed countries where the consumption of electricity has almost reached the saturation level.

Consumption of electricity is increasing steadily. The per capita electricity consumption in Kerala is also increasing steadily, but it is not at par with other parts of the country. The low load factor of the state is getting reflected here also. Lack of base industrial load, low agricultural load, predominant commercial and domestic load and high population density are the major reasons for the low per capita consumption. As the consumer profile is predominantly domestic and commercial, this growth in per capita consumption without increase in industrial consumption indicates the quality of life in general

Table 4.2 illustrates the growth in consumption within the control area.

Table 4.2 Kerala Power System – Growth in Consumption

Year	Consumption MU	Consumer strength (lakhs)	Per capita consumption kWh
57-58	363	1.1	19
60-61	518	2	30
73-74	2121	8	79
80-81	4499	16	109
90-91	5331	35	185
99-00	9812	60	300
00-01	10319	65	312
05-06	10906	83	314
06-07	11331	87	345
08-09	12414	94	375
09-10	13971	97	420
10-11	14548	101	436
11-12	15981	105	478
12-13	16838	108	501

The growth in per capita income in other parts of the country and the national average are above that of Kerala control area. This is more evident in the recent years.

Table 4.3 State-wise per capita electricity consumption

	Per capita electricity consumption in kWh				
State/ UT	**2012-13**	**2013-14**	**2014-15**	**2015-16**	**2016-17**
Chandigarh	1168	1133	1052	1112	1128
Delhi	1613	1446	1561	1557	1574
Haryana	1722	1773	1909	1936	1975
Himachal Pradesh	1380	1348	1336	13339	1340
Jammu & Kashmir	1043	1066	11699	1234	1282
Punjab	1761	1810	1858	1919	2028
Rajasthan	982	1011	1123	1164	1166
Uttar Pradesh	450	472	502	524	585
Uttarakhand	1297	1285	1358	1431	1454
Chhattisgarh	1495	1601	1719	2022	2016
Gujarat	1796	1973	2105	2248	2279
Maharashtra	753	764	813	929	989
Madhya Pradesh	1239	1183	1257	1318	1307
Daman & Diu	7927	8003	6960	7836	7965
D & N Haveli	14341	14515	13769	15137	15783
Goa	2045	2198	2203	2338	2466
Andhra Pradesh	1135	1196	1040	1230	1319
Telengana			1356	1439	1551
Karnataka	1129	1170	1211	1242	1367
Kerala	**630**	**645**	**672**	**704**	**763**
Tamil Nadu	1226	1544	1616	1688	1847
Puducherry	2136	1692	1655	1672	1784
Bihar	145	160	203	258	272
Jharkhand	847	810	835	884	915
Orissa	1209	1349	1419	1564	1622
West Bengal	594	609	647	660	665
Sikkim	862	700	685	687	806
Arunachal Pradesh	719	503	525	600	648
Assam	240	280	314	322	339
Manipur	353	266	295	310	326
Meghalaya	690	684	704	815	832
Mizoram	469	445	449	502	523
Nagaland	268	259	311	345	346
Tripura	296	331	303	329	470
Total(All India)	914	957	1010	1075	1122

From the table 4.3, it can be seen that though there is growth in per capita consumption within the state, the growth is comparatively low for Kerala state.

4.7.4 Consumer Profile

The consumer profile is a major factor affecting the consumption pattern. The impact of the consumer profile is more significant on instantaneous power rather than on the annual energy consumption. The instantaneous power requirement is the key figure in finalising the optimum long-term power procurement.

Table 4.4 Consumer Profile

Year	Consumption		Revenue	
	Industries	Domestic	Industries	Domestic
1970	61%	3.5%	27%	15%
1977	64%	10.5%	35.5%	18.2%
2013	29.63%	49%	37.84%	29.82%

From the Table 4.4, there has been outstanding increase in the share of domestic sector consumption compared to the industrial consumption. The industrial consumption recorded a negative growth. The increase in domestic consumption is corroborated by the fact that all villages in Kerala were electrified very early compared to other states [27]. However, though the increase in the share of revenue from domestic sector has increased, it is not proportionally. The revenue contribution by industries has increased in spite of the reduction in the share of consumption.

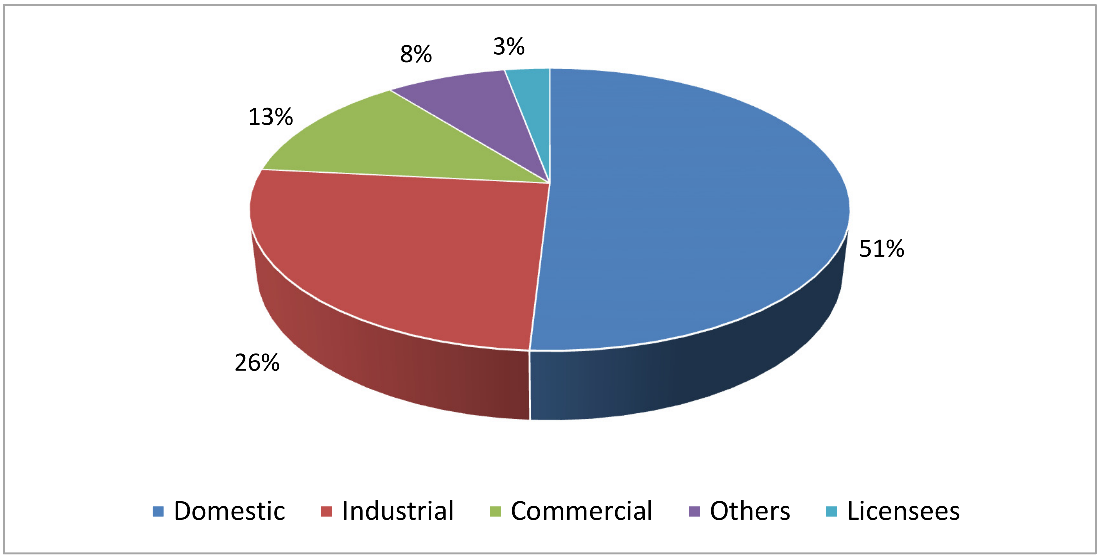

Fig. 4.4 Consumption Pattern 2015-16

The consumption pattern for the year 2015 –16 is shown in Fig 4.4. The domestic consumption has increased to 51% of the total consumption. Industrial consumption has reduced to 26%.

The revenue contribution from the industrial sector is still the predominant, in line with the actual consumption, though the growth in consumption is alarmingly low compared to those of the commercial and domestic sectors. The industrial consumers, being the most technically literate among the classes of consumers, have significantly improved the systems, thereby reducing the energy intensity. As the benefit of high hydro content has vanished in Kerala system, the tariff became comparable to other states and the energy intensive industries lost the charm of compensating other negative aspects of the state such as high labour cost, high land cost and transportation cost of raw materials. Such industries have withdrawn from the state.

The elasticity of demand is very less in domestic and commercial sector. It is very difficult to change the consumption pattern of the domestic sector with carrots and stick. Time of Day metering has been imposed on domestic sector wherever the consumption is more than 300units per month, but there has been no significant impact on the consumption pattern. In the commercial sector, which consumes about 13%, the consumption pattern is quite stiff. However, as the tariff is very high and the consumers are generally commercially oriented, solar PV with storage may find more penetration with such commercial consumers. The behavioural changes of domestic sector is another aspect. With the increase in per capita income, there has been improvement in the life style. The notable among them concerning electricity sector is the penetration of domestic air – conditioning. This has increased the night off peak demand, especially during summer season considerably. This has resulted in effectively compensating the fall in base load industries, thereby maintaining the overall load factor on annual basis.

Determination of electricity tariff were matched to the cost of supply of power and limits were put on the deviation of individual tariff classes from the average cost of supply by the 2010s. This has resulted in substantial increase in the domestic tariff and slow rise in commercial and industrial tariff recently. Even though the revenue contribution from the industries is still remaining highest, the contribution from domestic sector is growing at a faster pace.

4.8 CONCLUSION

The methodology to be followed for the SWOC analysis of power system on control area basis is analysed and the major points to be considered are identified. The methodology was applied on Kerala Power System as a case study. The study of Kerala Power System, observations and mathematical interpretations are done in this chapter.

CHAPTER 5

SWOC ANALYSIS & INTERPRETATION

5.1 INTRODUCTION

Based on the analysis and observations of Kerala power system, SWOC analysis from the perspective of optimisation of cost of power procurement for Kerala on annual basis is done. The major points are briefly narrated.

5.1.1 Strengths

The major strengths of Kerala power system from the perspective of cost optimisation are enumerated below

- Higher component of variable hydro generation.

  The hydro generating units are capable of varying generation from very low value to maximum rating in a matter of few minutes without any appreciable change in the cost of generation. For example, Idukki generating station, a single unit is capable of varying generation from 30MW to 130MW in about 2minutes. For the station as a whole, the variation in generation possible is 720MW (30MW one unit running to 750MW with all units running), which is possible in about 45-50minutes after the start of one unit. Normally during summer period, generation from Idukki varies from 30MW to 750MW in a day.

  The most important aspect regarding the hydro projects of Kerala is that except a handful of small projects, none of the projects are linked to irrigation. In comparison, though several other states have even higher hydro generation capacity available, the variability as per system requirements and commercial considerations of operation is much high in Kerala.

- The start-up time for hydro generators is very less. For Idukki generators, the typical start-up time is about 12minutes from the instant of start command to synchronisation. Same is the case with almost all other generators.

- The load factor of hydro generation is around 40%. For Kerala as a whole, this corresponds to a variation of about 600MW to 1200MW. This variability can be used for peak – off-peak demand variation which is about 1000-1500MW and for market operations.

- The thermal generation comprises of 230MW LSHS (Low Sulphur Heavy Stock) diesel which is capable of starting and stopping on daily basis. These machines are of 16MW/20MW unit rating, which makes it possible to keep the generation to the bare minimum considering the cost of generation.

- The absence of internal coal-based generation, or in general thermal generation which could find place in merit order, takes away the risks of the cost and availability of the fuel. However, it is to be noted that this is a strength as well as weakness, as the management of the base load generation are governed by the mutual agreements and regulations.

5.1.2 Weaknesses

The major points to be considered as the weakness of Kerala Power System when compared to similar control area are the following

- The internal generation is not sufficient to meet the demand. The state is dependent on import of power to the extent of 60-70% on annual energy requirement as per 2017 conditions.

- The state is devoid of coal and gas, which are the cheapest sources. The renewable generation potential (wind and solar) is also less compared to other parts of the country. The hydro generation potential could not be harnessed fully as the Western Ghats is declared as ecologically sensitive and fragile tropical forest.

- The internal generation is mainly hydro, the energy content is vulnerable to monsoon variations. The energy requirement met by the hydro generation is about 30-40% of the total consumption on annual basis.

- The state is having considerable forest cover. The density of population is also high. Barren land is practically nil. These facts contribute to difficulty in development of generation projects and laying transmission lines.

- The major share of available thermal generation is naphtha based combined cycle projects (around 500MW). The cost of generation is very high from naphtha sources. The variability of generation in combined cycle mode is also low. As a result, the operation of these plants is very low. As per the details available in the ARR [86], the load factor of these stations on annual basis is less than 30% for the last 5 years. This results in fixed cost liability for the distribution licensee.

- Consumption being predominantly domestic and commercial, the impact of weather and social events like holidays on the consumption is very high.

- Lack of industrial demand affects the base load.

- Low agricultural demand through dedicated agricultural feeders prevent the easy curtailment/ shifting of load that is possible in other control area in the country

- The peak to off-peak demand variation is very high. This results in low asset utilisation if the marginal demand during peak exceed the marginal hydro generation capability during peak. The penetration of solar PV without storage in large quantity in distributed generation may worsen the situation.

- The small hydel schemes are capable of generation during monsoon period only and are not capable of generation during summer, when the consumption increases. The number of storage type hydro schemes is only three.

5.1.3 Opportunities

Kerala Power System has many advantages which can be beneficially utilised if planned and operated properly. These include the following in the present scenario. It is to be noted that the opportunities are always dynamic and changes with respect to time.

- The capability of hydro machines with high degree of variability of generation in a very short period provides accurate control over load following. This is a major advantage in market operation. The variations in demand and the sudden outages of external power can be easily managed.

- Kerala being at the tip of the country, there is no chance of any transmission constraint caused by injection of power from Kerala. Market operation is favoured and benefit on account of market splitting may only aid Kerala.

- The storage type hydro schemes contribute about 40% of the total hydro power sources. This provides capability of hydro conservation during most of the time when bulk power market rates are low.

- The monsoon period and the low demand period coincides with the peak demand of the Northern Region, enabling swapping of power with such control area. There is practically no constraint in selling power from southern region and the transactions could really happen as soon as the import constraints of northern region are over.

- Effective real time market operation can reduce the overall cost of power procurement. The higher content of hydro energy makes it possible to optimise on the reservoir storage available with market operation.

5.1.4 Challenges

The optimisation of operation and encashment of opportunities is possible only by overcoming some challenges. The challenges are also quite dynamic and change with time. Any change in the network could change the challenges in short time.

- The Kerala control area is geographically isolated from the mainland with Western Ghats covering the boundary to other states. This limits the number of transmission lines that can be drawn to the state. The lines are passing through forests, which makes the construction, maintenance and rectification after a fault difficult.

- The consumer profile is mostly domestic and commercial and as the consumption increases, the present advantage of peak shaving with hydro reduces in future. This will have effect on reducing utilisation of the available assets. If additional capacity becomes necessary for peak management, contracting that additional quantum may be possible on round-the-clock basis only, which pushes up the cost of energy delivered in the control area.

- Increase in the penetration of renewable sources is limited on account of the already existing low load factor. Irrational renewable penetration would lead not only to technical issues in the system operation, but also commercial interests of all consumers.

- Heavy vegetation and difficulty in getting additional right of way for transmission lines results in criticality of the lines and the outage of lines may affect considerable load.

- Import capability is limited by the availability of interstate transmission system.

5.2 FINDINGS

The SWOC analysis of Kerala power system reveals the possibilities that can be adopted by the control area to optimise the operation of the power system. The major finding are furnished below.

- As the internal generation is stagnated, corresponding to the increase in the demand, the hydro power availability for market operation is diminishing. There is a need for optimising the power procurement to minimise the cost of the power procured for delivery within the control area.

- The contracts for power purchase have to be carefully finalised. The capability of the hydro potential to even out the differences in availability makes it possible to arrange firm power to meet almost the entire base load. Thus, it is essential to fix the base power contracts and peaking power contracts separately. Determination of base power requirement and peaking requirement is therefore crucial in the optimisation of power system operation. Forecast of energy on long-term basis is satisfactory, but the forecast of peak power requirement is to be improved.

- The generation from the hydro sources needs to be optimised for the lean inflow summer period, when the market operation with any surplus water will be beneficial. The reservoir management is to be optimised.

- The hydro generation is subject to the availability of water in the reservoir. Hence, there is a need for segregating the must-run and schedulable portion of the hydro potential available as on any day for enabling scheduling decisions.

- For scheduling activities and for ensuring the reservoir management optimisation, the hydro generation scheduling has to be delinked from peak-shaving and other thumb rule approaches and to be based on merit order based on the price of hydro generation. Procedure has to be developed for determining the price of hydro and to put it in merit order dispatch.

- The power procurement portfolio is to be optimised. The utilisation of internal generation has to be on merit order only. The internal naphtha and LSHS stations, irrespective of the ownership, have to be operated on commercial grounds only.

- The balancing power identification shall be made after meeting the power requirement and energy requirement for the control period. The balancing power can be negative also, in which case, the extra power available shall be operated as per the market conditions. Backing down can be issued only if the market rate is lower than the variable cost for generation from that particular source.

- In future purchase contracts with other utilities, the target load factor of such sources shall be minimum possible, at least aligning with the demand load factor.

- On long-term, the solutions include building up of storage mechanisms and construction of pumped storage schemes associated with the existing reservoirs. These are to be considered along with the penetration of solar generation and penetration of electric vehicles which have the potency to change the load curve significantly. This aspect is reserved for further studies.

5.3 CONCLUSION

The SWOC analysis is a powerful tool for strategy finalisation. The parameters selected for SWOC analysis has to be carefully chosen so as to represent the requirements. The SWOC analysis of the Kerala Power system is carried out and the opportunities to be pursued are identified. This information is used in the development of methodology for optimisation of the cost of power procurement for the Kerala control area in the subsequent chapters.

CHAPTER 6

LONG TERM DEMAND FORECAST

6.1 INTRODUCTION

The power system management is all about balancing of actual electrical load with the generation in real time. There are two aspects involved here – one is to ensure electricity availability for meeting the energy requirement for a control period, say, one year. The second is to ensure the availability of adequate generation capacity on bar to meet the requirement of electrical power at any point of time. In this work, the optimisation is done on the cost of power procured for distribution within the control area for the entire control period. Hence, no distinction is made between generating stations based on location of the generation plant as well as its ownership.

Electricity is being viewed as any other tradable commodity, but with the inherent characteristics as already pointed out in Chapter 1. . In order to meet the consumption of electricity varying over the day, the approach is to limit the long-term tie ups for the base demand, and to supplement the remaining quantity from variable generation potential as in the case of hydro generation and from short term market. The short-term markets are generally volatile, and can shift easily from a buyers' market to a sellers' market even on consecutive days. Hence, the quantity for such purchases is to be limited to the minimum possible as risk mitigation strategy, considering the probable depth of the market. Accordingly, the distribution utility has to have a combination of long-term power contracts and short – term power contracts. Hence, there is a need for long-term contracts and short-term contracts and the need for a better long term demand forecast.

6.2 NEED FOR BASE LOAD AND PEAK LOAD CONTRACTS – INDIAN SCENARIO

The price discovery in any market depends on the supply–demand balance and the price in the time domain is a function of the dynamic equilibrium of these two vectors. However, Indian electricity market has a long way to go for attaining maturity. Analysis of the price discovery mechanism of electricity in the past is interesting.

In the initial stages of the electricity industry, in 1890s, though the competition among the power generating companies were fierce, the cost remained very high. This was attributed to multitude of reasons, major of them being the capital intensiveness, limitation in the number of players resulting in cartelisation etc. By 1907, the regime of cost plus approach was established, accepting that the sector is a natural monopoly. Here, the price was regulated. In general, when the price of sale is regulated, there can be incentives for minimising costs or it can hold the prices down artificially. The major issue regarding regulated price is that if there is inefficiency, it will be paid either as tariff or as tax by the citizen. It is not always easy to identify inefficiency or force-majeure condition which may cause higher apparent costs. As the capacity of the electricity sector grew, the regulation became difficult. Government supports were often called, which meant the tax paid by the people went to sustain the electricity sector in addition to the tariff paid.

A good market can do control the prices by improving the efficiency and can take care of sustenance of the industry. Market based operation of the electricity sector was tried successfully in many countries, and there were a couple of pitfalls also. Taking cognizance of this, there was an attempt in India to open up generation for market operation by 1990s, as the transmission and distribution networks got strengthened which would be capable of taking the rescheduling requirements of the power system operation. In India, the concept of independent power producers (IPP) promulgated in early 1990s, however, did not prosper as planned.

It is also worth noting that the overall economy of operation could be achieved when the generators designed with higher efficiencies taking the benefit of sizes could increase in number. In India, the development of 1000/2000MW stations fuelled this, and soon after the declaration of open access of transmission system, ultra-mega power projects were also promulgated with capacity not less than 4000MW. Deployment of such high capacity systems required part of the capacity tied up under firm contracts and part for marginal market products.

The price of electricity depends on the time of utilization. However, price elasticity of electricity (as a commodity) varies with different consumer categories. Generally, consumption of electricity depends on several factors like weather, examination period, major sports events, festivals, nature of day etc. The variations in consumption are contributed mainly by the domestic sector, agricultural sector and commercial sector in varying degrees of response to each event. The response of industrial consumption is also there, but many of the major industries are immune to these issues. However, industries may be able to control the consumption of electricity if appropriate price signal is given. During the evening period after dusk, most of the applications in domestic sector, commercial sector and utility sector like street lighting etc. have practically no price elasticity.

In India, distribution utility is mandated to identify sufficient resources to meet the requirement of its consumers under all the conditions. Traditionally, the utility takes its own measures to construct a generating station. The opening of electricity market has facilitated the entry of distribution utilities to enter into contracts with generators on specific terms and conditions, which opens up umpteen optimization possibilities.

Construction of a conventional power plant and evacuation system for the electricity produced in the station is time consuming and implementation is much slower than the pace of growth of demand, especially in developing countries. Though the non-conventional sources such as wind and solar can be constructed at a pace almost matching with the growth of demand in developing countries, the vagaries of sun and wind makes it insufficient for meeting the demand for electricity. The planning of load-generation balance on long-term basis requires long-term load forecast. Several methods have been developed for long-term forecast. These are considered in Indian context in general in the national power survey reports which forecast the annual consumption and peak generation. A simple translation of the deficit during various periods vis-à-vis the availability from existing and on-going projects gives an estimate of the contracts to be considered for power purchase on medium term or long-term basis.

In capacity-constrained countries, the general approach in planning is to incentivize the generation addition. The detailed project reports for generation schemes generally conclude on the basis of the firmness of tariff, fixed either through regulation or through competitive bidding. The life of a power plant being 25-35years, factors like policy changes, availability and cost of fuel etc. are prominent risk factors. Some generating stations have been affected and are performing below the expected levels and even down to zero annual plant load factor. Such non-performing assets add the financial commitment of the beneficiary utility. Hence, for a distribution licensee, the commitment towards a long-term contract has to be carefully considered, in order to reduce the fixed liabilities in future. Any mismatch in the availability and consumption may lead to price shocks in the market. One way of alleviating such price shocks in the market is to enter into long term contracts.

6.3 MATHEMATICAL ANALYSIS OF PRICE TRENDS IN THE MARKET

In general, in long-term contracts, the buyer gets insulated from the market price fluctuations and the seller is reducing the risks of non-utilisation of assets during market slumps. As a result, the cost and price should ideally converge in such contracts. Any generating company, for survival, has to balance the expenditure and reasonable profit with the income generated from the sale of energy generated. The life of a generating plant being 25- 35 years, the investment is of very long period. There are risks associated with the changes in government policies, availability of fuel, technology changes etc. during this period.

Objective

To derive the pricing strategies and relation with the contract period.

Assumptions

The long term contracts means a contract to procure energy from a generating plant

- for a period in commensuration with its life and
- at a load factor near the optimum load factor of the generating station or loaded with additional compensation

Computation

Conventionally, the costing of generation from a plant is seen as a fixed cost, a semi fixed cost and a variable cost. Mathematically,

- The fixed cost (α), also referred to as overnight cost in economic terms, include the present value of the plant to be paid as a lump sum upfront to pay for its construction including rent of land, cess an royalty to the government and the salaries of the permanent staff. All expenditure irrespective of the maximum demand and number of units generated form the fixed cost component.

- The semi fixed cost, (β), is related to the maximum demand on the station, but independent of the energy generated. The maximum demand requirement fixes the maintenance of the plant, simultaneous requirement of generators on bar, requirement of fuel stock, maintenance staff requirement. Techno-economic issues in operation such as change in heat rate, number of start stops, cost of auxiliary power etc.

- Energy charges, (γ), sometimes referred to as variable cost also, depends only on the number of unit generated. This is contributed mainly by the cost of fuel and lubricants and all other expenditure which go into the operation of the plant. The variable cost component will be zero if there is no energy sent out from the plant.

From the first principles, the total annual cost C_a of energy for the any generating station is given by

$$\mathrm{C_a} = \text{Annnual Fixed cost} + \text{Annual Semi fixed cost} + \text{Annual Energy Cost}$$

That is,

$$C_a = \alpha + \beta kW + \gamma\, kWh \tag{6.1}$$

Where

α = annual fixed cost independent of maximum demand

β = semi fixed cost proportional to the maximum demand generated

γ = variable cost depending only on the number of units generated

The Indian regulations initially considered only two part tariff, but now considers a third component proportional to the maximum and minimum schedule obtained, number of start stops etc. as there has been several cases of partial load operation.

The average cost of generation per unit can be found by dividing C_a with the number of units generated for the year. Thus, the cost of generation per unit is dependent on the load factor also.

$$C_{pu} = C_a/kWh \tag{6.2}$$

From the definition of the load factor λ, number of units kWh can be expressed as

$$kWh = kW\ .\lambda.n \tag{6.3}$$

Where

λ is the load factor of the station and

n is the number of hours of the period considered for λ.

From (6.2) and (6.3),

$$C_{pu} = \frac{\propto}{kWh} + \frac{\beta\ kW}{kWh} + \frac{\gamma\ kWh}{kWh} \tag{6.4}$$

Substituting for kWh,

$$C_{pu} = \frac{\propto}{8760\lambda\ kW} + \frac{\beta}{8760\ \lambda} + \gamma \tag{6.5}$$

where the number of hours is 8760 (24 x 365) as the annual cost is taken.

From the above, it can be seen that C_{pu} is inversely proportional to λ. Minimising C_{pu} in equation (6.5), it can be seen that the minimum corresponds to λ =1 if no constraints are imposed on λ.

However, in actual practise, the load factor of the generating plant is never unity. The units will have to be taken on scheduled maintenance even if there are no breakdowns. This iis attributable to the generator. From the procurer side, there could be low demand period when the schedule given is less than the declared availability. Ence, it can be concluded that, in general, the higher the load factor λ, the lower is the cost of generation per unit. The minimum occurs when the actual load factor λ equals the optimum load factor λ_{opt} of the generating plant. Mathematically,

$$C_{pu} \text{ tends to minimum when } \lambda \text{ tends to } \lambda_{opt}$$

In practical case, purchase of power on long term contracts are usually finalised on the basis of two part tariff, with some technical limits imposed on the scheduling. The capacity charge is set to be fully recovered at optimum load factor λ_{opt}, usually 0.85 or 0.90. The variable charges are applicable for the energy scheduled. Thus, for a buyer, the annual price payable is

$$P_a = \text{Capacity charge} + \text{Variable charge}$$

Mathematically,

$$P_a = \tau \, . \, \lambda_{eff} . kW + \upsilon kWh \tag{6.6}$$

where

τ = Capacity charges paid proportional to the actual load factor

υ =Energy charges payable proportional to the units scheduled.

and,

λ_{eff} = 1 if the actual load factor is above the target load factor

= $\lambda_{actual} / \lambda_{target}$ if actual load factor is less than the target load factor and subject to the condition that if kW scheduled is always above the technical minimum scheduling in real time and kWh scheduled is above the technical minimum during a billing period.

Price per unit is obtained by dividing the equation (6) with the total scheduled kWh. From equation (6.6), it can be seen that as the actual load factor tends to target load factor, the price becomes minimum.

Deduction

By corollary, the long term purchase / base purchase shall be restricted such that the schedule is almost uniform to ensure high load factor.

Steps to solution

The utility has to develop a mix of contracts to suite the demand profile, which typically consist of base power and peaking power supply agreements. Optimisation of power purchase expenses of the distribution licensee thus requires of assessment of base load and peak load for the control period and sub control periods as required.

The approach developed here is to develop a method by which the long-term requirement for peak and base power requirement can be assessed for optimizing the long-term commitments.

6.4 LONG-TERM VS. SHORT-TERM COMMITMENTS

The distribution utility is duty-bound to manage load-generation balance. The requirement has two aspects – to meet the real-time demand for electricity and to meet the energy requirement for the whole year (control period). The planning has to span from the next moment to about 7-10years. The objective is to work out the imbalance that could occur in the system at any point of time. Once this is identified, the portfolio to meet the demand can be thought of. For planning purposes, the load-generation balancing problem is solved by splitting the energy balance and power balance separately and then integrating the two to obtain the final solution. The energy balance is usually done on annual basis so that the annual repetition characteristics of hydropower and other renewable power (solar, wind etc.) are also captured in the process.

The requirement of power varies through the year depending on factors like weather, festivities, examination period, major sport events, political reasons, economic growth etc. The pattern is generalized by observation. There is clear difference between the consumption pattern on working days and holidays. The difference again has direct correlation with the consumer groups predominant in the control area. Weather plays another significant role in explaining the variations in daily consumption particularly among the domestic consumers except in core urban area. The commitments by the supply utility shall take care of these general factors.

The long-term commitments ensure availability of power over a longer tenure. This usually goes with purchase of part or full capacity of a generating station or even the construction of a generating station. The benefits of ownership of capacity comes with a bouquet of advantages such as better control over availability of power, price of power tending to the cost of generation including return on equity etc. The most significant drawback in the case of thermal generation contracted in this manner is that the generation capability is uniform round-the-clock. Operational optimisation requires high plf (plant load factor) operation of the generating station. However, the demand varies throughout the day and the generation has to follow. Here, most of the authors load this variation in the tie line flow connected to nearby grid. The approach is not correct as the energy transaction through the incidental tie line flows caused by the variation in demand when the generation is held constant may result in sub optimal scheduling, especially when the pooled market to which the tie line flows gets accounted is cheaper than the cost of generation of the lowest cost generator in the portfolio. This could result in surplus during low demand period and hence under-utilization of the capacity and thus financial burden on the utility.

Another aspect to be considered while finalising the long-term contracts is the possible changes in government policy, fuel availability, fuel pricing etc. A typical example is the use of naphtha for power generation in 1990s. World over and in India too, a number of generating stations were proposed at that time and many of them were commissioned. Some of the late entrants had shelved the project and opted for other fuels. Naphtha was a cheap fuel earlier, but became costly due to technology developments in the petrochemical field that added value to naphtha. Some of the naphtha plants got converted to natural gas. The cost of natural gas has been falling internationally, but the price in India is much higher than the international price. The price of gas in USA is the lowest in the world and there is sufficient availability of gas in that continent and hence a comparison of the gas operated generating stations in India and USA is misleading. So is with other countries.

Any contract other than long–term is short–term. In the Indian regulatory lexicon, a medium-term product is also mentioned for open access transaction through transmission system. This is provided for a period up to 3 years. This product is developed with regard to the transmission system management and flexibility in scheduling. The priority for allowing power flow under different operational contingencies of line outages are made with respect to the type of open access. Even if a contract is entered for a period for three years or more, it is possible to schedule the power on daily basis or monthly basis also, which is a techno-commercial decision taken at the operation level of the buyer and the seller. In this work, the power purchase contracts are classified into two categories only – long term and short – term. This classification, as already mentioned, is based on the pricing logic, where the long – term contracts tend to settle at the cost of generation plus the return on investment and finance charges.

Short-term commitments, on the other hand, free the buying utility from several risks. The contract can be concluded only for the period for which it is required. The requirement could be seasonal, like the additional requirement for summer months in Indian context in general and Kerala context in particular. The requirement of power for Kerala in this manner may be limited to about 3 months from the middle of February. Another type of short-term power requirement is for meeting the diurnal variation of demand. The demand during peak hours varies widely from control area to control area. Even within India, there is significant difference in the load curve of control area like Kerala or Assam with that to Maharashtra, Delhi etc. The prominent underlying reason is the level of industrialisation. In comparison, the temperate zone countries have a drastically different load curve compared to tropic countries on account of the difference in climate. Normally for managing the variation in the load over the base load, the buying utilities go for short-term contracts. Here, the business risk is transferred from the buyer to the seller, which naturally tends to increase the selling price. In Indian conditions, the transmission network is also constrained and the national policy favours long-term contracts by providing priority in congestion scenarios.

The advantage of short-term trading is that by engaging in the short-term procurement plans, the capacity available with a merchant generator effectively becomes shared for different seasons and periods, assuming perfect diversity in requirement. For seasonal contracts, this is almost true. The demand in South India falls considerable with the onset of Monsoon by June 1st, starting from Kerala and spreading across the peninsula. The northern part of the country is reeling under simmering summer at that time and the respite comes only by July, when the monsoon becomes active there. The South needs power from November – December to about May, when the northern India is having pleasant climate and the consumption falls a little. There is a low demand period, say from July end to November, which can be utilised by the generators for annual overhauling works. Thus, there is a scope for the generators to operate for the buying utilities in the North and South as and when required. This results in overall reduction in the capacity charges to be paid by each distribution company.

Simple logical consideration leads to the conclusion that the long-term contracts shall be limited to a level where the variations in demand is optimally met through the variability of generation with due consideration of the financial impact on cost of generation at part load operation (technical limits) and the probable market operation with surplus or deficit created with such long-term contracts. In other words, the portfolio of the distribution licensee shall contain generating sources (including power purchase) having economic operational load factor almost equal to the load factor of the demand including short-term market operation.

Assessment of demand over long period is often done by several statistical and econometric tools. The assessment made predominantly using econometric methods in India has resulted in over projection of demand. It is interesting to note that the very purpose of long term forecast being to finalise the make or buy decision in arranging power, and the economy of operation being optimum when the load factor of generation and load matches, the impact of load factor is also to be captured in the forecasting process. The method developed here is to assess these depending on the index of utilization of grid viz. the load factor.

6.5 ASSESSMENT OF DEMAND

Assessment of demand for the purpose considered here encompasses the assessment of real time power requirement and the control-period energy requirement. The real-time power requirement has to identify the cardinal points – maximum and minimum demand that could occur in a day and in the control period as a whole. The variation of the maximum demand and minimum demand is also required to be captured. By definition, maximum demand is defined as the average demand in a period of 30minutes as per the present Indian regulations. The time period of 30minutes is almost universal, but some countries have gone for shorter durations recently. For the purpose described here, the average during 30minutes is quite insufficient. The power system shall be able to meet the demand that could occur even for a very short period so that the operational limits of voltage and frequency variations remain within the permissible limits.

Forecast of power requirement and energy requirement are interrelated. While accurate determination of power requirement is required for scheduling purpose on same day or day-ahead basis, the total energy requirement is of interest in long term forecast. Thus, though the latter is only a time integration of the former, the assessment methods are quite different. We have studied the outcome of several methods available in this area done for Kerala power system and Indian Power system as a whole. A simple method for replacing the econometric method followed for long term energy forecast was found necessary. The approach presented here is based on the load factor of the system, which covers the behavioural pattern of the consumers and the growth in demand as well. Forecast of demand using load profile method has been discussed in several papers. The method presented here is a modification of the load profile-based forecast to suit the requirements of portfolio decision making.

6.6 DERIVATION OF LOAD PROFILE FOR LONG TERM FORECAST

Demand forecast based on the forecast of turning points on the load curve and then producing the load curve with required granularity is referred to as load profile method. The cardinal points to the extent of 10 points per day is reported to have given good results. The load curve is then created from the forecasted points using profiling method. Thus the procedure is two stage, one to forecast the cardinal point and the second is the profiling for actual forecast. The whole method depends on a similar day in the past, it can be the previous day, the same week day last week or even last year.

Profiling can be accomplished by several methods, time varying splines, cubic splines, artificial neural networks, multiple regression models, judgemental forecasts, Box and Jenkins transfer function intervention – noise models etc. The different profiling methods give different curves. The forecast of the cardinal points can be done by any standard forecast methodology. The success of the profiling depends heavily on the selection of the similar day curve. The same week-day one year ago may be the best base curve in some case, but the same week-day of the previous week may be better suited for some other period of the day. In case of festivals, the similar date may have to be identified based on the festivity.

General modelling for load profile forecasting

Rather than choosing one similar day base curve for profiling, different base curves for parts of the day can also be chosen by regime switching models. It has been shown in theory that [21], [67], [100],

$$f(x,y) = I(\,x\ \in I_1)f(x,1) + (1 - I(\,x\ \in I_1)f(x,2) \qquad (6.7)$$

where,

I_1 is the regime and

f(x,y) is the forecast.

The regimes are taken such that *f(x,1)* is likely to be superior to *f(x,2)* in the selected time period. The choice of the regime is important in containing the error to reasonable limits. The criterion adopted is to choose the base curve as the one having similarity to the cardinal points forecasted. The difference is the change in the scaling rations which result from profiling. The change in scaling ratios at any point of forecast can be defined [21] simply as

$$\Delta ratio_x = \frac{1}{2}(ratio_{x+1} - ratio_x) + \frac{1}{2}(ratio_x - ratio_{x-1}) \qquad (6.8)$$

When several such forecasts are made with different similar curves, accuracy of forecast can be improved by combining these. This can be achieved by averaging or by optimisation through regression. Regression method is useful, but there could be multi-collinearity problem. One method usually adopted is to avoid negative weightages.

The conventional profiling techniques gives more importance to derive the forecasted load curve and is suitable only for short-term load forecasting. It is difficult to achieve the desired accuracy on annual scale. Hence modification is needed.

Modification to the general load profiling method

In this work, the reproduction of the exact load curve is not intended. The approach developed is to forecast the demand in a long – term demand horizon and that too for determining the peak and base power requirement. The long term power purchase decision do not require the minute to minute variation in the demand to be forecasted. This is covered in the short-term forecast and real – time forecast, which are used for scheduling. The issue to be addressed was to reduce the error in the presently used methods of econometric and other hybrid mechanisms of forecasting the peak power requirement and energy requirement. Such forecasted values are found to have serious errors.

The contiguous duration of almost equal demand is taken together to limit the number of iterations. In the case of Kerala power system, nine such time zones have been developed, 00:00hrs to 02:30hrs, 02:30 to 05:30hrs, 05:30 to 07:30hrs, 07:30 to 09:45hrs, 09:45 to 13:30hrs, 13:30 to 17:00hrs, 17:00 to 18:30hrs (except during winter), 18:30 to 23:00hrs and 23:00 to 24:00hrs.

It is pertinent to note that the demand is not changing abruptly during the transition time, but changes gradually. The point to be considered in the transition is the ramping rate of demand. Special considerations are to be taken in the load generation balance portfolio if the ramp rate is very high.

There are changes in the above timings during the year on account of weather changes and lifestyle changes (e.g. during the month of Ramzan, the demand rises above normal from around 03:30hrs and falls to normal by 05:30hrs, during examination periods, the evening peak extends to late night etc.). These changes in demand is to be net from the Balancing Power, which is not considered here. Several techniques have been developed and deployed for estimating the load profile on short-term basis, of which relaxation techniques and ANN methods give good results.

Load forecasting methods using relaxation techniques and ANN methods is not appropriate for longer time span extending several years, which is to be considered for arranging power purchase contracts. A practical approach is developed here, which is simple to apply and giving fairly good results. The method is also based on some assumptions specifically derived from the SWOC analysis of Kerala power system.

6.7 ANALYSIS OF LOAD CURVE

The pattern of consumption of electricity varies from consumer to consumer. However, within a category of consumers, the consumption pattern is almost the same. For example, the consumption pattern of industries is quite forecastable and the consumption is uniform on round-the-clock basis or for predefined time. The industrial consumption is not vulnerable to weather unless there are interruptions in electricity or transport. The consumption pattern of business establishments is almost the same, but peaking from mid-day to night. The consumption of domestic consumers can also be well predicted with peak consumption in evening and morning, and forecast can be improved if the class difference of consumers is also factored, say generally as high consuming group, upper middle-class group, lower middle-class group etc. The load curve of the control area is the collective consumption behaviour all consumers. There are some tariff-based tools normally employed throughout the world to incentivise the consumption pattern suiting to the most economic supply of electricity. As the load curve of the control area is the collective response of all the consumers, it is logical to conclude that the load factor of the system remains almost the same unless there are substantial changes in the social and economic front of the control area affecting the consumer profile significantly.

From the SWOC analysis, the consumer profile of Kerala is showing declining trend of industrial consumption and increasing component of domestic consumption. Combined with this, the change in the behavioural pattern of domestic consumption is also to be seen. The per-capita consumption has increased despite the falling contribution from industrial consumption in Kerala. This indicates that the domestic consumers in Kerala have improved their lifestyle, depending more on electricity for the energy requirement. Naturally, the consumption during night off peak hours increase with the increasing penetration of air-conditioning. This has led to a situation where there is not much difference in the load factor of Kerala control area.

The demand of the control area is essentially a function of the real - time consumer mix. This consumer mix varies seasonally also. For example, the air-conditioning load in the domestic sector is not active during monsoon and winter seasons, but much significant during examination periods and summer. The pumping load is definitely seasonal. The industrial and commercial load has dependency on the day – on holidays and festival periods, the industrial load will come down. These aspects are considered in day-ahead scheduling and real-time system management. At the planning level, the nitty-gritties are to be filtered off by averaging so as to enable the planner to see the forest as forest. The question is how to average. The averaging shall maintain the information on the variability of demand. This is achieved by dividing the day into different time blocks and then averaging the demand over the third dimension, i.e. the days. We have divided the day into ½ hour time blocks, with 48 data per day. This is then averaged on annual basis and plotted. Thus, each point in the graph is the average of 365 data points. This means the analysis of 17,520 data for each year. It may be noted that the data taken from 2006-07 to 2009-10 (old data) is purposeful to demonstrate the usefulness of the model developed for the subsequent years and also to show that the same is valid even after a period of about 10 years.

The annualized average load profile of Kerala power system is given in Fig 6.1.

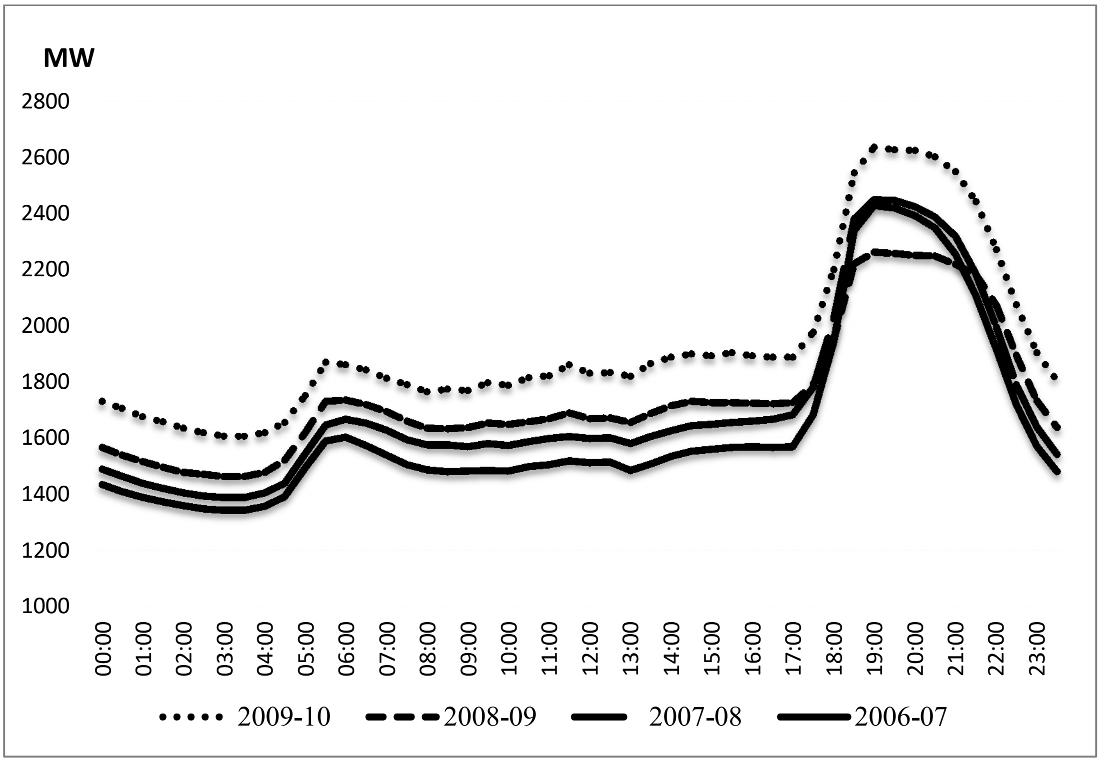

Fig. 6.1 Annual Average Demand

From fig 6.1, there has been no significant variation in the load curve except for lateral shift, in commensuration with annual consumption increase. There is a change in the pattern during the year 2008-09, and this is attributable to the load shedding to the extent of 10% of the peak demand during evening peak for the entire summer. The load interruptions on day-to-day basis, resultant of any difference in the load generation balance is normally filtered off. Hence there is no need of finding out the unmet demand in the analysis.

Analytically the load factor of Kerala power system for the period from 2005 to 2011 shows arithmetic mean of 76.48%, median of 70.09% and standard deviation of 3.84%. The load factor of the period under consideration is tabulate in Table 6.1.

Table 6.1 Analysis of Load factor of Kerala Power System

	2008-09	2009-10	2010-11	2011-12
Maximum	0.849038	0.841965	0.888352	0.866229
Mean	0.764808	0.774778	0.770607	0.780989
Median	0.758948	0.721591	0.735807	0.748806
Minimum	0.648747	0.640109	0.665434	0.661831
Standard deviation	0.035491	0.034152	0.035537	0.030467

Thus, load factor is a key indicator to determine the load profile corresponding to the energy requirement. Hence, if the annual energy consumption is estimated, the load profile can be estimated without much difficulty, assuming a practically constant load factor. It was seen that the method was successful and gave fairly good results, which is discussed subsequently.

6.8 JUSTIFICATION FOR ADOPTING ANNUALIZED AVERAGE

In the foregoing analysis, the annualised average demand is taken. There could be apprehension on using this data for determining the power purchase portfolio as it could lead into surplus during some period and deficit during some other period. The classical approach had been to restrict the long-term contracts to the minimum demand for the control period. In this approach, the market portfolio was not seen considered as a potential profit centre. Unutilised capacity was considered as a cost centre.

The peculiarities of the control area are also important in this decision making. In general, the availability of hydro power is one of the critical figures that decide the purchase requirement, though the sensitivity decreases with the increase in consumption. The spatial distribution of monsoon plays an important role in month-to-month purchase plan. Variability in demand and supply co-exist and in most cases, these are anti-complementary, viz. a lower availability is usually accompanied by a hike in demand, widening the load – generation gap in real time. Thus, a reduction in monsoon not only reduces the availability but also increases the consumption, resulting in wider gap between demand and availability. Here, in case the gap is significant to affect the cash flow issues and the financial stability of the distribution licensee, ultimately resulting in increase in tariff, the possibility of declared restrictions on usage of electricity, which is commonly referred to as load shedding and power cut is thought of. Thus, the short-term changes are managed by additional purchases, changes in the scheduling of existing contracted generators or by coercive action on the demand side. In classical approach, the marginal demand during peak period of the year is to be solely met from short-term contracts.

The intention here is to segregate the quantity of power to be availed on short – term and long – term basis. Long-term contracts provide power for a period of 12 years or more as per the present regulations. Normally, the contracts come to a cost-plus pricing policy if the contract period is just above the debt recovery period. In some cases, covering the entire life of plant may be beneficial when the costing is done.

In any case, the long-term contracts cover a number of years. The long-term purchase requirement is decided considering the minimum and maximum demand that could occur in a control period. Minute variations are therefore not required in long-term purchase plan and averaging is considered sufficient and suitable.

6.9 CASE STUDY MODELLING

The modelling and sample forecasting has been done for Kerala system as a case study. The forecasted figures have been checked with the actuals and found to be matching for the purpose of arranging the power purchase. The derivation of the logic and the computation method are described in this section.

The first step is to form the load duration curve from the load curve. Load curve shows the demand in the system on chronological order. As shown in Fig. 6.1, in general, the demand is the lowest in the night off peak hours, increases to a morning peak by 6:30hrs to 7:00hrs. After morning peak, again there is a trough and then the peak demand occurs after dusk. In order to further analyse the requirement of purchase of power to balance the energy requirement, this graph is plotted in the same scales, but after arranging the demand from the highest to the lowest. This graph indicates how long the load sustains at each level and gives direct visualisation of energy requirement of energy. The load duration curve for a typical case of 2009-10 is shown in Fig. 6.2.

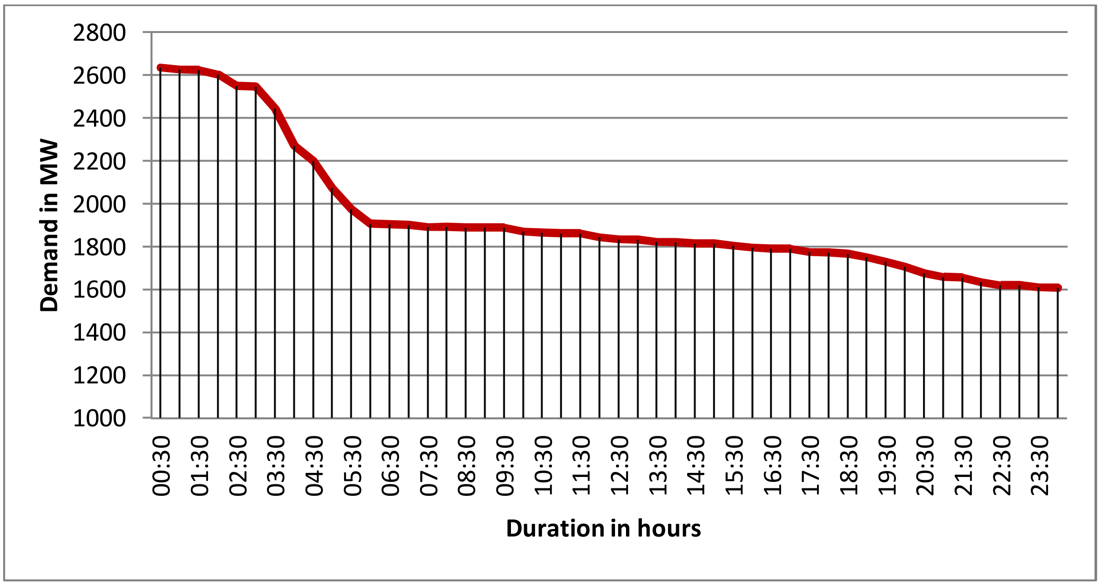

Fig. 6.2 Load Duration curve (2009-10 data)

From the load duration curve, the base load is around 1600MW, indicated by the solid thick green line, which is the minimum demand incident on the power system. The typical peak demand in the vicinity of 2500 – 2600MW remains for about 4 hours a day. The demand varies between 2500MW to about 1900MW for about 2 hours. Majority of the period, the demand varies from 1900MW to 1800MW. For further processing to a simple mathematical model this curve is linearized indicating the average figures. For analysis purposes, we are maintaining only two figures, peak demand which sustains for about 4hours and an average demand which last for about 20hrs. The two figures taken for the analysis are the average corresponding to the time bocks taken.

In case the minimum demand alone is taken as the base demand, it may result in too much short-term power requirement, probably increasing the cost. Further, the minimum demand occurs for a very low period of time and that too for a few days. On all other days, there could be a deficit in availability of power. To obviate these issues, the average of the rest of the peak period is taken as a flat figure. This is shown in Fig. 6.3.

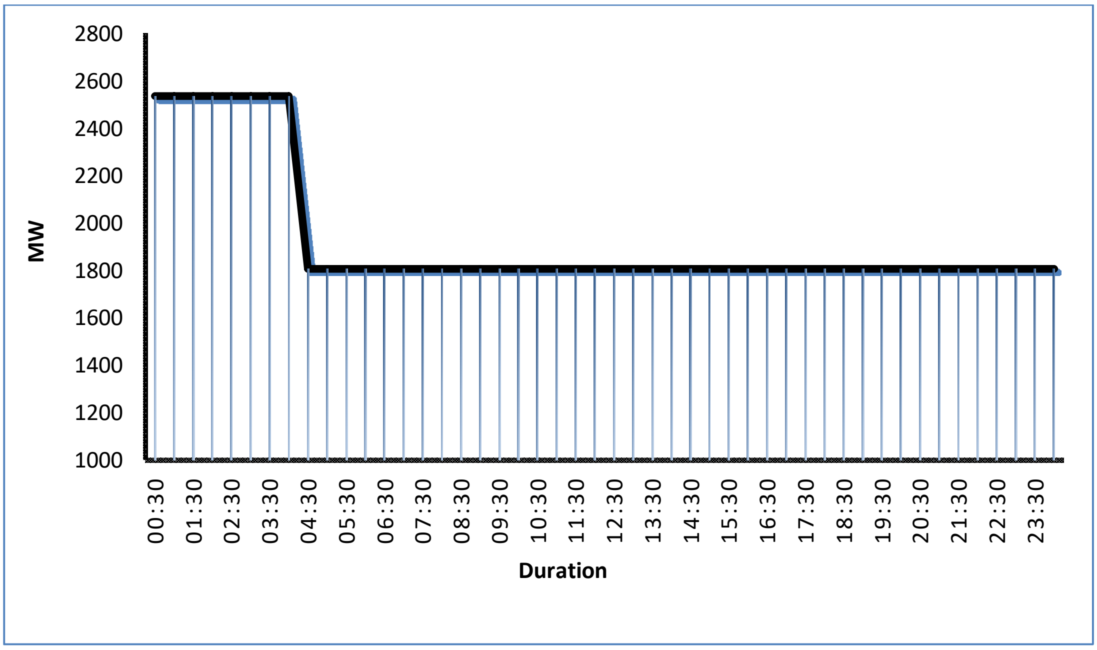

Fig. 6.3 Linearized Load Duration curve (2009-10 data)

With this, some of the salient relations are derived.

Let

E = Energy met for the day in MWh

E_{Base} = Base Demand in MWh

E_{BP} = Marginal Energy component constituting the peak in MWh

P_P = Average demand during Peak hours in MW

P_o = Average demand during other than Peak hours in MW

h = Duration of Peak demand in hours

λ = Load factor

$P_{H\text{-}d}$ = Daily generation possible from Hydro sources in MWh

$P_{H\text{-}Base}$ = Base hydro generation in MW

$P_{H\text{-}Max}$ = Maximum Generation possible from all hydro stations during peak in MW

$E_{H\text{-}Base}$ = Daily base generation possible from Hydro sources in MWh

Total energy E served for a day in the control area is then computed by integrating the area under the curve. Thus, the energy E is the integral of peak power P_P for h hours and off peak power P_O for (24-h) hours.

$$E = \int_0^h P_P dt + \int_h^{24} P_O dt$$

$$= P_p * h + P_O * (24 - h) \tag{6.9}$$

By definition of load factor,

$$E = P_P * \lambda * 24 \tag{6.10}$$

From (6.9) and (6.10), it can be shown that the average demand except during peak hours

$$P_O = \frac{P_P * (24 * \lambda - h)}{24 - h} \tag{6.11}$$

This corresponds to the linear lower portion of the linearized load – duration curve shown in Fig. 6.3. In other words, this P_O corresponds to the average base load of the control area on annual basis.

Base Energy $E_{Base} = P_O * 24$

$$= 24 * P_P * \frac{24 * \lambda - h}{24 - h} = \frac{E}{\lambda} * \frac{24 * \lambda - h}{24 - h} \tag{6.12}$$

For deriving the peak load requirement from the above, the Marginal Energy component constituting peak E_{PM} is derived as follows:

$$E_{PM} = E - E_{Base}$$

From (6.10) and (6.12),

$$E_{PM} = 24 * P_P \left(LF - \frac{24 * \lambda - h}{24 - h} \right) \tag{6.13}$$

From this, the various figures for finalising the power procurement can be computed.

6.10 APPLICATION OF THE MODEL AND VALIDATION OF ASSUMPTIONS

The model developed above can be extended to any year as long as the load curve retains the approximate shape as assumed. The extension of this method done from the year 2011-12 is elaborated as case study.

The annual load factor based on the past figures is taken as 76.5%. The assumption that the annual load factor remains without much deviation is established with the actual figures during the study horizon. Hence this proves the validity of the assumption.

The annual energy requirement projected for the year 2011-12 was 19235MU. These figures are considered by KSEB in the Aggregate-Revenue-Requirement petition filed before the State Electricity Regulatory Commission. From the load curve and load duration curve, the peak duration is about 4hours. The expected figures are, therefore, computed from the above formulae as follows:

$$\text{Daily average Energy requirement}, \mathrm{E} = \frac{19235 * 1000}{365} = 52699\mathrm{MWh/day}$$

$$\mathrm{E_{Base}} = \frac{\mathrm{E}}{\mathrm{LF}} * \frac{24 * \lambda - \mathrm{h}}{24 - \mathrm{h}} = \frac{52699}{0.765} * \frac{24 * 0.765 - 4}{24 - 4} = 49461\mathrm{MWh/day}$$

$$\text{Base power requirement } \mathrm{P_O} = \frac{\mathrm{E_{Base}}}{24} = 2060\mathrm{MW}$$

$$\text{Average Peak power requirement } \mathrm{P_P} = \mathrm{P_O} * \frac{24 - \mathrm{h}}{24 * \lambda - \mathrm{h}}$$

$$= 2021 * \frac{(24 - 4)}{(24 * 0.765 - 4)}$$

$$= 2870\mathrm{MW}$$

Comparison of results

The actual demand on half hourly basis for the year 2011-12(17,520data points) was analysed in detail. The cardinal values are consolidated in Table 6.2

Table 6.2 Load forecast: 2011-12 Actual demand summary

Peak conditions	
Annual average of peak demand	2856MW
Maximum demand met in 2011-12	3346MW
Median of the peak demand for the year	2835MW
Minimum of the peak demand	2221MW
Other than peak conditions	
Annual average of other than peak demand	2023MW
Maximum of other than peak demand	2846MW
Median of day time demand	2120MW
Minimum demand for the year	1681MW

The computed results and the actuals for the period upto 2016-17 are tabulated in Table 6.3. The actual load factor is varying across the years due to impact of monsoon on the consumption, scarce summer rains increasing summer peak demand, good summer rains dampening summer demand etc.

Table 6.3 Comparison of Demand - Actuals and Forecasted for 2011-12

	Actual	Computed
Annual average of peak demand	2856MW	2870MW
Annual average of other than peak demand	2023MW	2014MW
Total energy for the year	19235MU	19087MU

Variations in the actual figures are contributed by the intentional intervention on the supply side by the distribution utilities, natural calamities leading to load crash, monsoon failures leading to abnormal increase in load factor, load shedding during peak hours due to contingencies in the power system etc. However, for long term planning, these effects can be neglected. The variation in actual load can be managed in real time situations by suitable rescheduling.

Table 6.4 Comparison of long term demand forecast and the actuals for 6 years

Year	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
Forecasted consumption MU	19235	20400	20504	21536	23151	23501
Actual Consumption MU	19087	20053	20758	21734	22836	23819
Computed average peak demand MW	2870	2985	3104	3228	3357	3491
Actual average peak demand MW	2856	2906	3035	3156	3295	3404
Actual load factor %	76.11%	78.54%	76.19%	75.71%	77.19%	78.91%

The comparison of the long-term forecast results as per the method in this work and the actual demand is given in Table 6.4. It can be seen that the method is efficient.

For further validation of the method developed, comparison of the forecast made by the conventional method and the forecast as per the method developed in this thesis are furnished in table 6.5

Table 6.5 Comparison of long term demand forecast by different methods

Year	Demand in MW					
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
Actual average peak demand MW	2856	2906	3035	3156	3295	3404
Forecasted demand (MW) as per conventional method	2950	3097	3252	3414	3585	3765
% error	3.19%	6.18%	6.68%	7.58%	8.11%	9.59%
Computed average peak demand MW as per the method developed	2870	2985	3104	3228	3357	3491
Actual average peak demand MW	2856	2906	3035	3156	3295	3404
% error	0.49%	2.65%	2.22%	2.23%	1.85%	2.49%

6.11 CONCLUSION

The peak demand assessment is essential for the determination of the contracts to be engaged by the distribution licensee for providing power to the consumers. Such contracts for power purchase/ investments for own generation entails a fixed charge commitment, optimising this is critical in the optimisation of cost of power procured for the control area. The method developed has been successfully giving results for the assessment of peak demand and energy requirement on annual basis.

CHAPTER 7

MERIT ORDER PRICING OF HYDRO GENERATION

7.1 INTRODUCTION

The most significant issues in the hydro – thermal coordination and merit order scheduling stems from the difference in the treatment of hydro generation and thermal generation. As already narrated in detail, the problem was circumvented in several ways, most of them with heuristic thumb rules, which have the tendency of convergence to local optimum. When the fixed capacity charge for hydro generators is fixed as in the case of thermal generators, the energy charges become very low, and the hydro units always come in the must – run generation category. This method, hence, do not capture the benefits of hydro generation potential.

Migration of merit order from cost basis to price basis is found to be sufficient to solve the issue. However, the price of electricity is variable and hence the potential price for the hydro generation is to be taken prudently. Further, for the same hydro generating station also, the price has to factor the reservoir storage position, anticipated inflow etc. and is therefore dynamic. The method developed for pricing hydro generation is discussed in this chapter. The pricing of hydro for the purpose of optimisation of operation from grid management point of view is to split the total hydro generation capability into must-run and schedulable. This “merit order pricing” has nothing to do with the pricing for commercial settlement of hydro generation from each plant. The words “price” / “pricing” used in this work refers to “merit order pricing” unless the context means otherwise explicitly.

7.2 NEED FOR MERIT ORDER PRICING OF HYDRO GENERATION

Merit order considers the generation which matches the cost of the marginal generation which fills up the load generation balance portfolio for unit commitment and changing the schedule of generation from the running unit. When the portfolio consists of hydro, thermal, nuclear and renewable sources for meeting the demand of the control area, the cost alone cannot be taken for the purpose of unit commitment. The way out is to impose technical constraints in the optimisation program. These technical constraints include must-run nature of the plant, technical minimum limits of generation, transmission constraints modelled by market splitting etc.

It is an accepted fact that the cost of generation from hydro power plants is very low compared to other sources. If that alone is taken, entire hydro generation gets scheduled first, by which we cannot ensure that the resource utilisation is optimum over a control period. The issue with the hydro power plants is in the variability of availability of water. For thermal and nuclear plants, if the availability of the generating unit is ensured, the generation is possible at any time, as arranging fuel is a controllable task, though the cost may vary if the transportation from alternate mine is longer than the normal coal linkage route. In the case of hydro, dependence on inflow is the key point, on which there are no practical control. For Kerala system, the dependency is on monsoon and by the end of the active monsoon period, i.e. from June to November, almost 82% of the inflow is received. The normal design plant load factor of a hydro station could be around 30 – 40% compared to the target of 85% - 90% for coal-based generators.

World over, conventionally, hydro machines find application in peak load management. In literature, the optimum scheduling considers peak shaving with hydro. This is based on various factors such as controllability, lower start-up cost, fast loading capability, reduced start-up time, comparatively high cost of market power during peak hours etc. The potential of the market was not fully exploited in this approach. The thermal generators were planned to operate at high load factor and as base load. Without any exception in countries world over, low load factor operation of thermal generators was considered as a sin till very recently. This is evident from the archives of tariff orders of NERC in USA, CERC in India, ENTSO in Europe etc. Now, there has been a need for shift in this approach due to the increasing RE penetration. To compensate the RE injection, the thermal generation has to be backed down during some period. Hydro, with its inherent capability of economic operation at low load factor, find application in the balancing requirement generated by the RE generators in addition to the traditional peak shaving attribute. For the purpose of scheduling, the merit order requires price based on which unit commitment and generation scheduling can be carried out. Hence, there is a need for determining the price of hydro generation under various scenarios, which has been developed here.

7.3 MERIT ORDER PRICING OF HYDRO GENERATION

The regulatory approaches in almost all countries for determination of tariff for hydro station converge on the concept of primary energy and secondary energy, usually decided on a certain percentage of average inflow into the catchment area. This concept covers the expenditure of the generating company and reduces the amount involved in truing up in subsequent years. The dependency of hydro generation on the inflow and the very low cost of generation compared to the method adopted for the determination of variable cost for thermal generators makes the tariff unsuitable for forming the merit order stack. However, the concept of primary energy charges and secondary energy charges can be best utilised by a hydro generation company for optimising its availability declaration when operated as a merchant plant. This approach will not result in optimisation of scheduling on control area basis.

The merit order pricing of hydro for the purpose of optimisation of operation from grid management point of view is to split the total hydro generation capability into must-run and schedulable. The categorisation is basically dependent on the capacity of the reservoir and the installed capacity of the generating station.

7.4 CATEGORISATION OF HYDRO GENERATION AS MUST – RUN AND SCHEDULABLE

Some of the hydro generating stations are inherently must-run. By must-run, what we refer is that if the water available is not utilised for generation immediately, it will be lost either as spill over of the reservoir or will have to be released from the reservoir for any other purpose, such as irrigation or for drinking water processing. In the case of must-run condition, the hydro generation from such generators is to be scheduled irrespective of the load generation balance with thermal generation on bars.

The must – run status is dynamic, especially if the project is associated with smaller reservoirs. The typical situations arise when the catchment area has very high rate of precipitation for some time of the year and the storage capacity of the reservoir is limited due to one or another reason. The inflow available may be sufficient for peak load operation during lean inflow period, but the reservoir may be in spill threat or in spilling condition during high inflow period. In such cases, the project could find place in the must run category for some period of the year and moves out of the category when the season changes.

Another case of must – run condition arises when a generating station is operated as part of an irrigation scheme or drinking water scheme. Here, the reservoir storage is controlled by the irrigation department or water authority as the case may be as per the requirements of the water. Little scope is left for optimisation of storage or generation in such cases. Here, the must-run remains only for a certain predetermined quantity of water, and the remaining water if any, forms part of schedulable hydro.

The generation from a hydro generator in the must-run category is not sensitive to power system requirements. Hence, the generation is to be treated as available at the cost of generation so that in the merit order dispatch, it always finds place in the scheduling. The merit order price of hydro generation in such cases is to be treated as zero.

However, if there is no tag associated with the water stored in a reservoir, the generation can be ensured at any point of time in the year from the generating projects associated with such reservoirs. The generation from such generating stations can be scheduled as per power system operation requirement. This forms the schedulable hydro generation. Merit order price has to be determined for such hydro generation.

7.5 MERIT ORDER PRICING PRINCIPLE

The generation schedulable from such hydro stations can be utilised at any point of time. That means, such hydro generation is suitable for reducing the power availed from the costliest source at any time during the year. Hence, leads to the conclusion that the price of the storage available in such reservoirs, in other words, the price of the generation from such hydro generating stations, is equal to the highest cost of replaceable energy during the entire control period. This is the Merit Order Price of generation from the particular generating station at the particular time.

Thus, the pricing of hydro generation is dependent on

- the type of reservoir to which the plant is attached – storage type or run-of-the river type
- the rate of inflow and the storage at that particular time – in other words dynamic with respect to the weather and the time of the year
- other contractual obligations of the reservoir – such as irrigation reservoir or part of drinking water project

Based on the above, the merit order price of hydro generation can vary from 'zero' rupees per unit to the highest cost energy that could find scheduled in some period of the control period. By this method of pricing, the issue of assumptions in hydro generation like reservation for peak shaving, reservation for sudden ramping etc. is solved.

7.6 OPTIMISATION

Existing mathematical model and limitation

The optimisation of the cost of power procurement on control area basis and control period basis is not attempted adequately in text books. The classical approach is to model the thermal generation with quadratic function and to use blinds for peak shaving using hydro. The concept of peak shaving emerged as the merit order is based on the cost of generation. The non-peak hydro, if any, is treated as a must-run with hydro generation in the optimisation problem solving. Further, the hydro component in the total energy mix of the control area is often very low, say to the order of 30%. Hence, in some text book approaches, the cost function for the power delivered in the control area is taken as the quadratic function, which is applicable in general to the thermal generation [6], [25]. The optimal solution is arrived by minimising the cost function.

$$\lambda i = \alpha n + \beta n P ni + \gamma_n P_{ni}^2 \quad (7.1)$$

where

P_{ni}	=	Active power from the n^{th} generation unit during the i^{th} time block
α,β,γ	=	Cost function of the generating units in service, including the start stop cost under normal pattern of operation

The text book approach is to minimise λi. This can be achieved through any standard method.

The model assumes the entire hydro for peak shaving and the remaining must-run. This approach may result in sub optimal solutions. In actual practise, the above proposition on hydro management results in a high level of subjectivity. One of the major aims of this work was to develop a method by which this subjectivity could be avoided. Another drawback is in the reckoning of the hydro capacity irrespective of the inflow conditions.

The concept of peak shaving for scheduling of hydro generation is no more valid when optimisation is considered with availability of power from market, provided the market has sufficient depth. The cost of power in the market need not be the highest during peak demand period of a control area when several control areas are interconnected and with market permeable across these control areas. Hence even if the demand is high during evening peak, optimisation of price of power procurement may justify procurement of power during evening peak than resorting to 100% hydro generation. Thus, there is a need for optimising hydro generation by other means.

Thus, the problem is to identify the must – run condition of hydro generation schemes and to identify any impending constraints if the present pattern of generation is continued and to maximise the storage when there are no impending constraints so as to make use of convenient and profitable market conditions.

Solution methodology

No work could be traced to effectively deal with this aspect other than formation of rules depending on experiences. The mathematical models used in some of the approaches are too complicated with a number of data requirements, which are seldom possible in real life.

Optimisation is done on a reservoir model. The model considers normal statistical figures for forecasting expected inflow into the reservoirs. The rate of inflow will be time dependent and can also be forecasted.

In short, the optimisation works as follows: If a generator is not in must-run condition, the water in the reservoir can be conserved when the price of power in the market is less than the expected maximum price for the control period so that the water conserved is utilised effectively. This assumption leads to the optimisation of storage in the reservoir at any point of time.

The assessment of spill threat can then be used to determine the maximum storage achievable during the active inflow period. The possible extreme contingency anticipated in real time conditions is evaluated and the storage optimisation within the control period is worked out. The model developed in Microsoft Excel predicts the maximum storage that can happen and the spill threat of the reservoir.

The underlining assumption is that the changes in the reservoir storage do have a finite delay for change and the response time of generators is much shorter than that so that the depletion rate can be modulated fast. In a situation where this modulation is not effective, that hydro station is to be categorised as a must-run station, at par with wind and solar generation. That means, a hydro plant may be under must-run category for some period of the year only. Determination of the schedulable component of hydro depend on the storage available, rate of inflow, anticipated future inflow and the depletion capability of the station. As per the statistical data available for Kerala, even the largest reservoir in the state had instances of must – run conditions for a limited period of time.

The control period is subdivided for ascertaining the price of hydro in storage type reservoirs. Normally the apportioning is done with respect to the inflow pattern.

The problem attempted here is to determine the hydro generation target on daily average basis during each sub control period to arrive at P_{ni} so that the overall economy is reached for the control area during the control period. This requires a detailed study of the inflow pattern and reservoir characteristics. This is demonstrated through the case study of Kerala.

7.7 ILLUSTRATION WITH CASE STUDY

ALGORITHM

Step 1: Study the causative monsoon pattern

Step 2: Deduce the inflow pattern from Step 1

Step 3: Model the reservoir and develop the water balance equation

Step 4: From the water balance equation, deduce the essential condition for spill

Step 5: Based on the result of step3, identify the status of reservoir. Reservoir can be classified into groups

Step 6: Evaluate the effects of parameter variations on the result

Step 7: Deduce the result

The algorithm is implemented and detailed in 7.7.1 to 7.7.7

7.7.1 The Monsoon

The Monsoon is a characteristic weather phenomenon, with strong influence in India and particularly in Kerala. Monsoon is traditionally defined as a seasonal reversing wind accompanied by corresponding changes in precipitation. The Monsoon starts in Kerala by June 1st with strong wind from south west and subsides after the North-East monsoon by November. Almost 80% of the annual inflow is received during this period from June to November in Kerala. The inflow to the reservoirs after December till May is nominal and the storage at the end of November is a key indicator on the performance of system operation. The inflow for the period from December to May is not very significant. Inflow modelling is done for optimising the operational strategy.

7.7.2 Inflow modelling

Though the unit of inflow is volume and is usually expressed in Million Cubic Meters (MCM), this unit cannot be used in the present analysis as the energy content of water varies from reservoir to reservoir. In order to make uniformity in the units and to enable mathematical operations on the inflow, the inflow is converted to equivalent generation in million units (MU) possible from each generating station. In the case of cascaded schemes and schemes having tail race generation schemes, the computation on the equivalent MU become tricky. To circumvent the problem of additionality, the MU equivalent is computed as Gross MU, which includes the possible generation potential from the downstream generating stations and Station MU, which is used for planning the generation from the particular plant. In the case of tailrace projects, the inflow to the main reservoir alone is to be considered. However, for downstream stations having pondage, the inflow to the local reservoir is also to be considered. Modelling of inflow is done using statistical data for each reservoir.

The monsoon has shown decadal pattern, though not very much demarcated. The initial approach was to take 10-year average for forecasting the inflow. In view of the trends, this is modified with ten year moving average. The moving average method is done on monthly data, but, deviations are profound on monthly data as per actual figures. Hence, the moving average figure on month-over-month basis is modified by applying corrections during monthly review of inflow. This continuous process is found to be giving good results. The modified moving average method is adopted in this work. Mathematically, the inflow I [i] for the i^{th} month of the year is given by

$$I[i] = \textit{Average of } I[i] \textit{ for the last 10 years}$$

7.7.3 Reservoir Modelling

Reservoirs vary in size and in the spread of catchment area. The generation is planned considering the characteristic of the reservoir. In general, the hydro plants are planned for achieving annual plant load factor of 30-40% in 90% favourable year. For operational analysis, the reservoir modelling is expressed by the general water balance equation, derived from the fundamentals as

$$\Gamma_0 = \Gamma_{-1} + I_{-1} - \vartheta_{-1} - \zeta_{-1} - \delta_{-1} \tag{7.2}$$

where

Γ_0 = Present storage

Γ_{-1} = Storage at the beginning of the control period, can be one day, month or year as the case of analysis

I_{-1} = Inflow during the control period

ϑ_{-1} = Depletion of water during the control period (Same as the water equivalent of generation during the control period)

ζ_{-1} = Spill during the control period

δ_{-1} = Evaporation and other losses of water from the reservoir during the control period

7.7.4 Water conservation

When the inflow to the reservoir is more than the depletion of water through generation, the storage increases and we say that water is being conserved. The conservation is generally done during monsoon period, so that water is available in the reservoir for summer season. In practical consideration, the evaporation and other losses δ_{-1} are negligible compared to the other terms and can be omitted.

Mathematically, water conservation in the reservoir is possible by keeping the rate of depletion $d\vartheta/dt$ below the rate of inflow dI/dt. The water level in the reservoir increases and the spill threat to be identified. From the basic principles, spill threat occurs when (ϑ_{-I}) remains negative consistently, say for η days such that

$$(\Delta I - \Delta\vartheta) > \Delta\Gamma \tag{7.3}$$

where Δ indicates the change in η days and

$\Delta\Gamma$ is the difference from the Full Reservoir Level (FRL) and the reference day's level.

Maximum storage occurs when the level reaches FRL and can be sustained if the depletion required ϑ per day is not more than the depletion capability of the generating station given by the product of installed capacity with 24 hours. With the given conditions, the storage can be increased by reducing the depletion to the 'safe level' such that $(\Delta I - \Delta\vartheta)$ remains under control and spill do not occur.

The objective function is to avoid or minimise ζ_{-1}. Taking the derivative of equation 7.3 with respect to time, we can see that the spill minimisation occurs when the rate of inflow and rate of depletion is equal and storage approaches FRL.

Mathematically,

$$d\vartheta/dt = dI/dt \quad \text{and} \quad \Gamma \rightarrow FRL \tag{7.4}$$

$d\vartheta/dt$ depends on the availability of generation capacity at the station and I is the hydrological parameter of the reservoir, including the catchment area, rate of rainfall etc. The conditions in equation 6.4 lead to classification of hydro stations based on reservoir capacity and depletion capability for the purpose of storage optimisation.

7.7.5 Classification of Hydro Generating Stations

The water balance is satisfied when $\Delta\Gamma \leq (I_{-1} - \vartheta_{-1})$ under maximum storage conditions to avoid spill ζ. Therefore, conservation of water (storage) is maximised when $\Delta\Gamma$ is minimum. The storage can be increased if ϑ is comparatively higher than the expected I. Thus, the characteristics of the reservoir are determined by the catchment area, rain yield and the generation capability (or more precisely, depletion capability). Based on these the reservoirs in Kerala were classified into three categories, viz. Group I, Group II and Group III.

Group I stations are characterised by reservoir with sufficient storage so that generation is possible during the summer period when the inflow is very less. They also offer flexibility of operation during monsoon period. Group II stations are more of pondage type, but forms part of cascaded schemes where the water from upstream storage type reservoirs can make them available for generation in limited scope during the summer period. They are typically operated as peak shaving stations during summer period. The third group are almost run-of-the river projects. Among these, only group I stations are of significance here due to the possibility of storage conservation.

The expected inflow (I) to a reservoir is variable over time. During the peak of Monsoon, the value of I could be very high and dI/dt changes sign very frequently. When dI/dt is positive, the ϑ_{max} shall be the limiting factor. However, ϑ_{max} is fixed with respect to the annual yield and the minimum load factor for the economy of operation. Spatial variation of I is the next important parameter and the modulation of ϑ with respect to the anticipated movement in the variation of I can bring in good results.

7.7.6 Analysis of Parameter Variations

The daily inflow into the reservoirs for the past 15 years was analysed in detail. Though various methods for daily inflow forecast are attempted, the forecast results have not been satisfactory for the entire Monsoon period. The meteorology department also has not been able to forecast the Monsoon availability for the whole season with satisfactory accuracy. The long-term forecast made by the Indian Meteorology Department (IMD) is considering a larger geographical foot print and often results in wide variations with actuals at control area level. For instance, in several years, the forecast of normal monsoon has been true for the country as a whole, but had significant variation for Kerala. The inflow further depends on still smaller catchment area, the possibility of error further increases. The forecast for the next 4-8 days as given by the meteorology department with reasonable accuracy is not sufficient to optimise the storage as the storage optimisation is to be done on the seasonal basis with maximum storage attained towards the end of the active Monsoon period. The reason for the errors in the overall monsoon prediction being cited is that the Monsoon is a complex process with umpteen parameters, all of which are not even identified. Cases of monsoon starting normal and later weakening due to cyclonic movements resulting in uneven distribution of rain is observed.

The most common methods for inflow forecast include 10-year moving average (MA) which is basically based on the correlation with cyclic nature of monsoon. As part of further improvement, attempt was made with 20 year moving average forecast, but the results are almost similar. The 10-year MA forecast is found to be delivering reasonable results when correction factor is applied during the progress of the season based on the current trends. This 10-year MMA (Modified Moving Average) method is adopted for study in this paper and is currently used in KSEB for inflow forecast.

The impact of the spatial distribution of inflow to each reservoir was further analysed. Fig. 6.1 shows the 3-dimensional graph of the inflow to a typical reservoir in Kerala. The Reservoir A selected is the largest in terms of capacity, catchment area and depletion capability in Kerala. The application of the proposed methodology is best illustrated with the reservoir chosen. The pattern is similar for other reservoirs also.

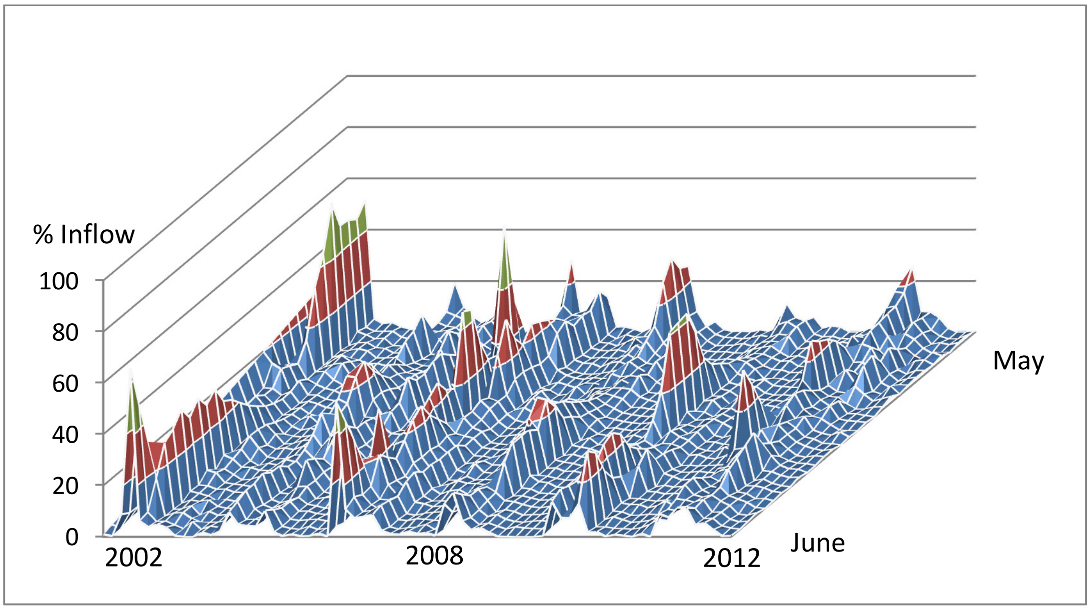

Fig. 7.1 Spatial Distribution of inflow as % of monthly inflow - Reservoir A

As evident from Fig. 7.1, the inflow is not uniform throughout the year. Further, the inflow has peaks in between followed by lean period even during high inflow period (monsoon period). Detailed statistical analysis was carried out on the data for 10 years. The period from 2002 to 2012 has been chosen so that the validation of the method could be done for subsequent years with the actual data available.

7.7.7 The 70% - 10 Days Rule

In order to optimise the storage at the end of the active monsoon period, the modified moving average method can be used reasonably. However, to estimate the probable daily inflow and to relate it with the depletion capability for the estimation of spill threat, detailed analysis was done on daily data. Statistical analysis showed that in a month, the highest inflow can occur on any day, but the monsoon activity and the resultant inflow to the reservoirs has inertia. The inflow on immediate succeeding days after a peak daily inflow also shows comparable inflow. This was identified as a credible contingency for ascertaining the spill threat of the reservoir.

In order to analyse, the daily inflow was computed to each reservoir. This was then sorted on the descending order of daily inflow and further normalised with respect to the maximum inflow for the month. The worst case observed was that about 70% of the monthly inflow is delivered in about 10days. This is observable from Fig. 7.2, which is inflow-day graph, where the daily inflows in each month are plotted from the maximum to minimum. It can be further seen that the peak is more during the monsoon period and flattens towards May, flatter during the summer period.

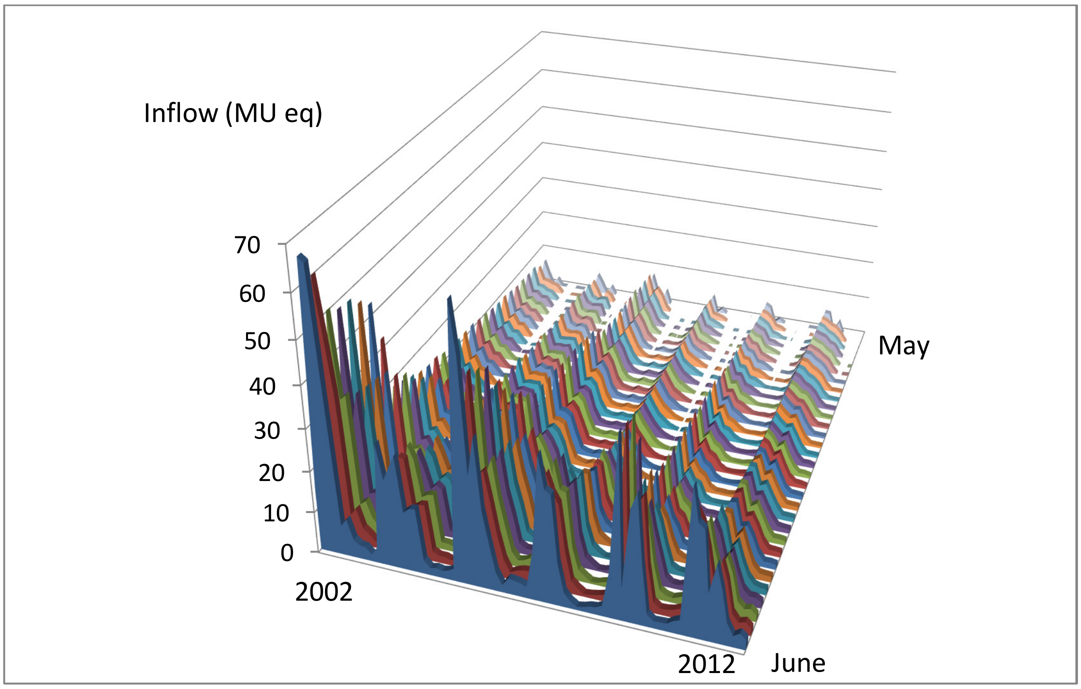

Fig. 7.2 Inflow -day graph - Daily inflow - Reservoir A

This behaviour is justified by the very physics of monsoon also. Monsoon is caused by the changes in the wind flow which carries a lot of water vapour and precipitation occurring when it crosses the land area and slows down. The wind force is not uniform, the speed and direction are based on the low pressure and high pressure created in some parts of the atmosphere. Torrential rain may result in the pressure difference path. In the extreme case, if there is a severe low pressure elsewhere, the wind direction may get altered, often resulting in monsoon failure. Because of these, the monsoon performance in peninsular India and All India has been different. As Kerala lies fully on the Western part of the Western Ghats, a peculiarity of the state, the impact of monsoon may vary significantly from the All India monsoon forecast. All these indicate that the rainfall in monsoon is not continuous, but in sprouts depending on the pressure difference in the atmosphere and wind speed and direction.

Whether the inflow received on a particular day is the maximum for that month cannot be determined definitely. Determination of safe level can be done only with this information. As the spatial variation of monsoon is rather very common, it is always possible that averaging of the peak inflow in every month may result in sub-optimal strategy. The short-term generation planning is first attempted on monthly basis. The credible worst case is that the maximum inflow period starts from the 1st of the month. Generalising, this is equivalent to considering the maximum inflow in a period to start with nth day. In order to avoid a chance of spillage, the depletion possible plus the possible rate of increase in storage upto FRL shall equal the rate of inflow.

The daily inflow to a reservoir for two consecutive months are plotted in Fig 7.3 and 7.4.

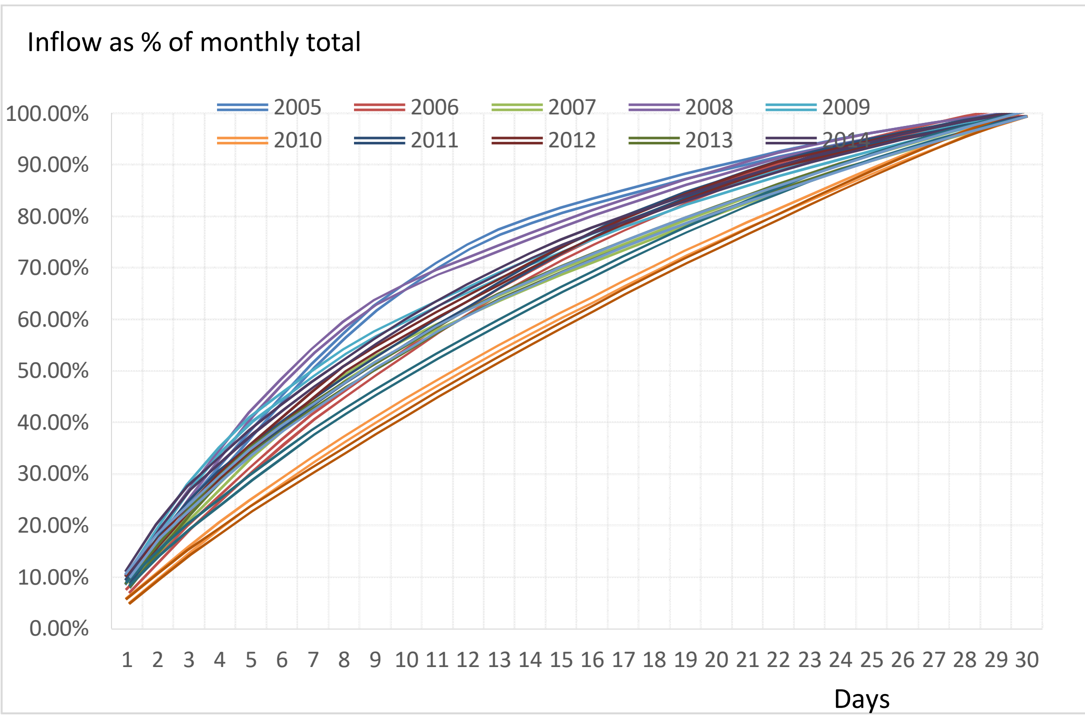

Fig. 7.3 Daily inflow in September – Reservoir A

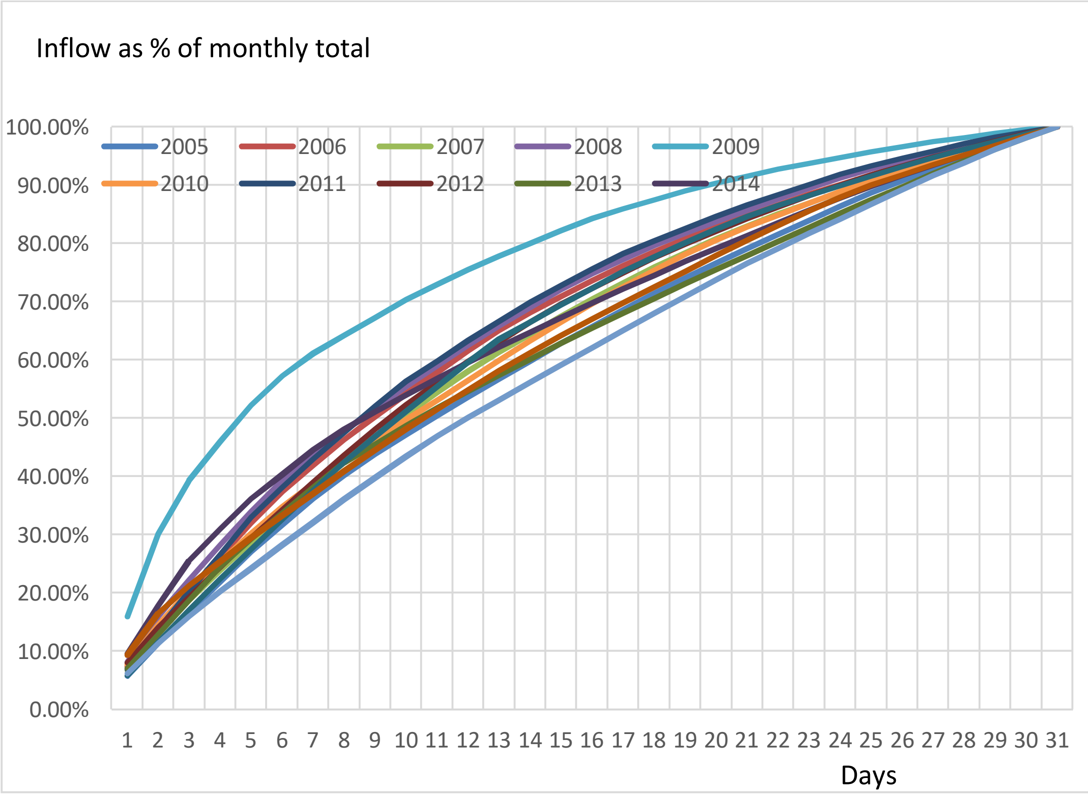

Fig. 7.4 Daily inflow graph Reservoir A- October

7.8 RESERVOIR STORAGE OPTIMISATION

The basic assumptions made in the model and the key observations from the data analysis are:

i. Active inflow period (Monsoon) starts on June 1st. The analysis of the date of onset of monsoon for the last 50years as per the details available with SLDC, Kerala and the meteorology department web site has shown that the maximum delay for onset of monsoon in Kerala is 18 days from June 1st. The earliest onset is 2nd May during this period, 30 days prior to the assumed onset of monsoon, i.e. 1st of June. For about 85% of the cases analysed, it was observed that the monsoon commenced on June 1st with a deviation of 7 days on either side.

   In general case, the significant day is the date of commencement of active inflow period. In case a demarcated active inflow period is not discernable for a control area, this date can be considered with respect to the beginning of any sub control period, say first of a month or any date in a month. The only point is that the inflow details pertaining to the control area should be available for such sub control periods.

ii. The initial storage for the sub-control period is to be fixed. This is fixed on the basis of statistical reasoning and thumb rules will be available.

In the case study of Kerala, for managing the grid management in the month of June till the monsoon strengthens require a carry forward in the reservoirs at the end of the control period, i.e. as on 1st of June every year. Carry forward requirement at the end of control period is determined on empirical rules. This is arrived as follows:

The demand in Kerala control area is having high dependency on the monsoon, partially on account of the consumption pattern of domestic consumers and partially on account of the damages caused to low tension lines during heavy monsoon period, especially during first rain due to heavy vegetation. But till the monsoon strengthens, the consumption remains high as it is an extension of the summer period. As per the historic data for the last 50years, the latest date for the monsoon to gain strength is 18 days. The carry forward is generally maintained to meet a high demand for 20 days from June 1st.

iii. The effect of constraints is to be considered in the real time operation. However, in the planning stage, no constraints other than availability of the generating units in the station are considered.

7.8.1 Mathematical modelling

Assumptions:

Carry forward water as on 31st May (end of water year)	X1
Water availability as on 1st June of current year (beginning of planning period)	X2
Maximum generation capability per day from the station during no maintenance	U1
Maximum generation capability per day from the station during maintenance	U2
Storage at the beginning of each month	S[1] to S[12]
Monthly 10-year moving average inflow	I[1] to I[12]
Spill expected/actual	Sp[1] to Sp[12]
(Spill expected is taken from historical data)	
Daily average generation pattern for each month	g[1] to g[12]

(g [i] is to be obtained from the energy balance for the entire year considering the availability from various other sources as well. Rough estimate using previous years' generation pattern is adopted for zeroth iteration)
Check whether the generation pattern thus fixed is less than U1 or U2 respectively.

Generation pattern for each month	G[1] to G[12]

Objective

$$S[i]end = X1,\ \sum Sp[i] \quad minimised \tag{7.5}$$

7.8.2 Computation algorithm

Step 1: Storage at the end of the month S[i]end is given by

$$S[i]end = S[i] + I[i] - G[i]] - Sp[i] \tag{7.6}$$

The computation is repeated for all the months i=1 to 12. The generation g[i] is initially assumed from historical figures.

Step 2: Check whether the computed storage S[12] = X_1.

Step 3: If Sp[i] is positive for any i, g[i] shall be equal to U_1 and maintenance period to be shifted one row above or below.

Step 4: Check whether the computed storage S[12] = X_1

Step 5: Modify the values of g[i] so that positive Sp[i] is minimised and compute S[i] for values of i upto 12

Step 6: Repeat Step 4 and Step 5 till S[12] = X_1

Step 7: Repeat the calculation when the actual data for a month is obtained by filling the actual data in the respective columns for g[i], S[i], and Sp[i].

Step 8: Repeat steps 4 to 6

The resultant vector at the end of Step 8 will give the optimum hydro scheduling for the sub control period at any point of time.

7.9 TYPICAL CASES OF SPILL THREAT ANALYSIS

The spill threat analysis is worked out as often as required and the minimum generation level is fixed. One typical case study carried out is shown graphically in Fig 7.5.

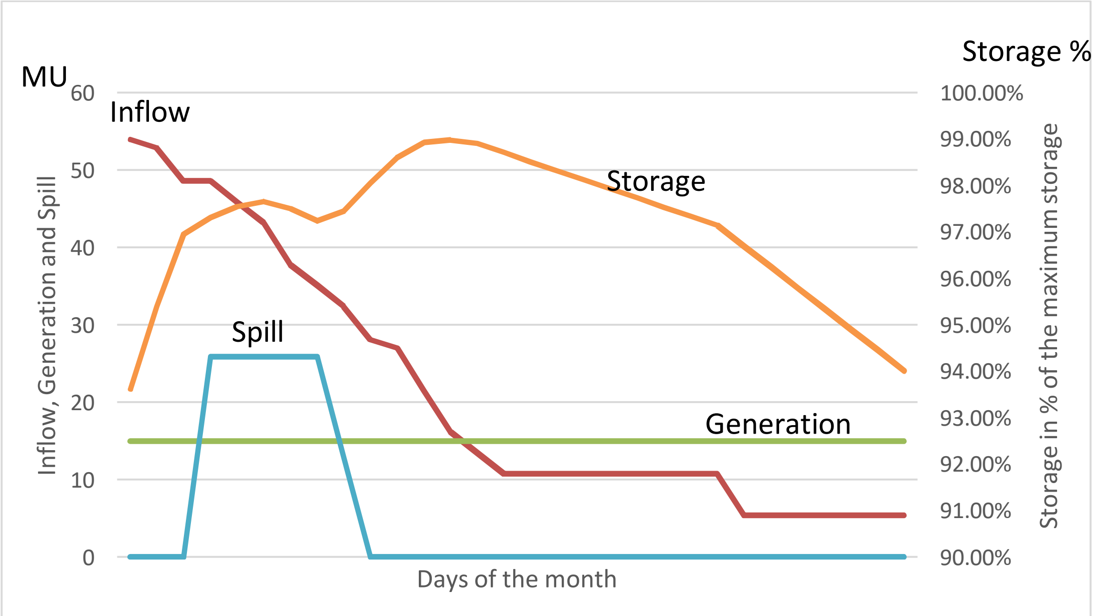

Fig. 7.5 Spill threat assessment and spill requirement computation

From the figure, with storage about 94% at the beginning of the control period and the inflow as shown anticipated, the storage would go beyond 100% by around 4th day. In order to contain the storage within permissible limits, spill has to be permitted for a few days. However, if the maximum inflow occurs on a subsequent day instead of 1st, the spill may not be required at all. Thus, this analysis gives indication for preparedness for opening the spill ways of the reservoir.

In this example, generation is assumed constant. This is so because the initial storage assumed is high and is in a must-run condition. In case the initial storage is, say, 80%, the margin available in the reservoir is more; the generation can also be controlled. On the other hand, if the generation can be increased by rescheduling planned maintenance, this gives the tool.

7.10 ANNUAL OPTIMISATION

The application of the above model in the reservoir storage management leads to the annual optimisation of storage and thus hydro generation. The price trend of the power in balancing market is generally high during lean monsoon period due to high demand in South India and extends to around June end when the demand of North India soars. Hence, maintaining maximum possible water level in the reservoirs at the end of active monsoon period is required.

The computation as described in 7.8 leads to the concept of safe reservoir level at the beginning of each sub – control period. In this works, we have taken monthly control. If the storage is remaining less than the safe level during monsoon period, water conservation is attempted whenever the market rates are less than the ticked rate. There has been significant improvement in the storage towards the end of the control period irrespective of the actual inflow to the reservoirs over the years. The details are furnished in Fig 7.6

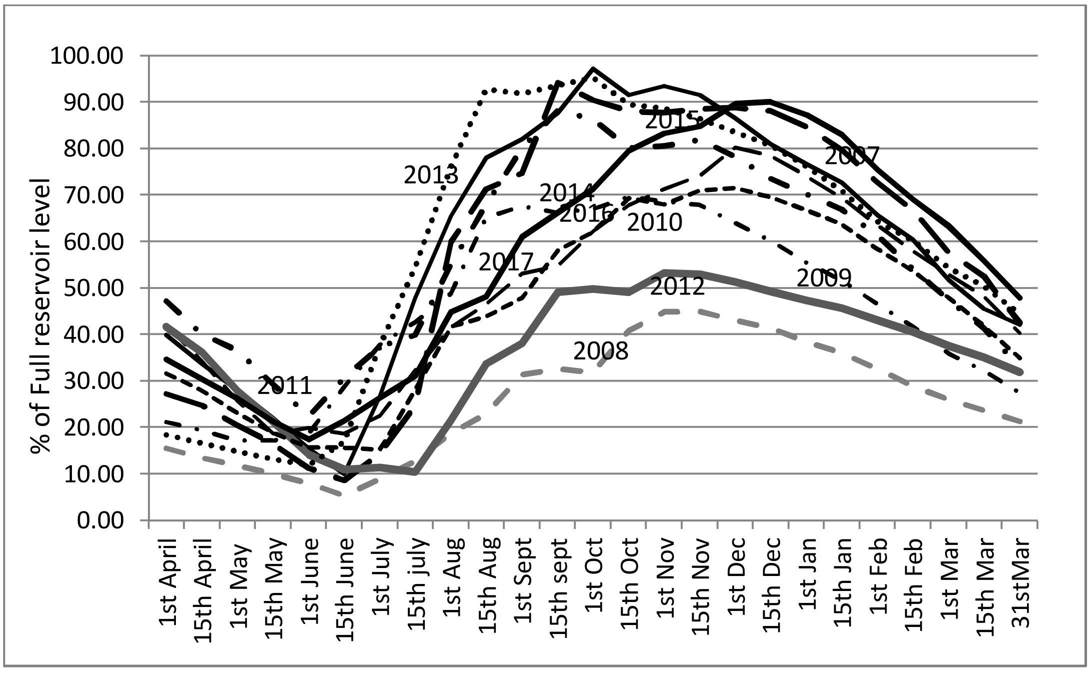

Fig. 7.6 Daily Storage at Reservoir A - 2007 -2017

From Fig 7.6, it can be seen that there has been increase in the % water level achieved in the reservoir (name kept anonymous as per the data sharing conditions) towards the end of the monsoon period. With this method, the storage could be built up during the active inflow period and could be sustained till the end of monsoon period. It is also worth noting that the storage could be brought to around 70% even when the inflow was about 48% of the normal. This has been possible by the adoption of the method described above.

7.11 CONCLUSION

The method developed has been applied in the system which yielded good results with the test data of Kerala system. The hypothesis of 70% - 10 days is validated for Kerala and has to be checked for other control area.

CHAPTER 8

OPTIMISATION OF COST OF POWER PROCUREMENT

8.1 INTRODUCTION

The cost of power procured for delivery in the control area is dependent on the power procurement portfolio. The consumption of electricity in the Indian context is increasing steadily and hence the power requirement. This means that the utility should have power supply contracts which will become effective progressively year over year. The new sources could be own generation plants with progressive commissioning dates, which are considered at par with a third-party generator in this analysis. The concept of peak shaving with hydro is basically on account of the high ramping possible. With the increased penetration of wind and solar generation, the ramping could be more severe than the peak hours demand ramping. The conventional method of assigning balancing power requirement and peak load requirement on hydro generation is likely to result in local optima when the market forces are also considered. It follows that even if there is energy deficit for the control period as a whole, it may be necessary to sell as well as purchase power for achieving optimum economy.

8.2 PORTFOLIO MODELLING

The basic portfolio finalisation is based on the cost of the power delivered in the control area. Three types of contracted sources are considered in the portfolio, viz. base power, peak power and balancing power. The cost of electricity delivered within the control area for a period of one year (control period) is represented as

$$P_E = \frac{P_B E_B + P_P E_P + P_{BAL} E_{BAL}}{E_B + E_P + E_{BAL}} \qquad \text{(Equation (3.1))}$$

Where

P_E = Price of energy supplied withinthe control area

P_B = Price of power contracted as base power

P_P = Price of power contracted as peak power

P_{BAL} = Price of balancing power

E_B = Energy served as base energy

E_P = Energy served as peak energy

E_{BAL} = Energy served as balancing energy

The solution is arrived by minimising P_E, subject to the constraints.

Constraints

The constraints can be classified broadly as Supply side constraints, Demand side constraints and Transmission side constraints.

Supply side constraints

Each source of power has its own characteristics with specific commercial implications and other ramifications. The merits and demerits of each source of power is to be analysed before finalising the portfolio. The major technical aspects involved are: the start – stops permissible, peaking capability, technical minimum generation possible, and availability of primary energy source and dependability of primary energy source etc. Depending on the source, these are summarised as follows:

- Coal based generators are capable of variation in generation without appreciable change in heat rate, and hence variable cost, in about 80% to 100% of the capacity. The start – stops are limited in view of technical reasons affecting the life of the equipments including boiler lines and increase maintenance cost affecting the capacity charges (fixed cost). The peaking capacity from coal based stations is thus, limited. The availability of coal is often affected by various reasons. Dependability of the coal based station with respect to the availability of power is comparatively high. Reduction of generation upto 55% has been made mandatory in India now (implemented from 2017) by providing additional compensation to the generators to cover up the expenses of secondary fuel consumption, increased auxiliary consumption and reduction in overall efficiency.

- Nuclear generation is treated as base generation where rate of change in output is much less than the system dynamics. There is no peaking capability. Fuel availability and dependability are not matter of concern. New generators are being designed with the possibility of variation of generation. However, apprehensive approaches of the nuclear plants make their operation stiff and operate at almost constant load well below their installed capacity.

- Hydro generation is capable of quick ramping from minimum to maximum and is characterized by very small technical minimum generation. The start – stops are also permitted as start-up and shutdown costs are negligibly small. The availability of water is the primary concern and depends largely on inflow. Dependability is quite high. The issue with the hydro generation is usually associated with the discharge commitment of water from the reservoir.

- Gas based source is comparatively better than coal-based source in terms of operational flexibility. However, if the generation is on combined cycle, the technical requirements are stringent. The exact figures for variability may vary depending on the unit size, cost difference between open cycle and combined cycle operation etc. The availability of fuel is not a matter of serious concern, but the costing of gas is a matter of serious concern. Further, the obligation of take-or-pay insisted is to be considered. The availability of market power is quite high and new projects have the minimum gestation period.

- Renewable energy sources are increasing in a large way in the installed capacity. The variability of the power and low forecastability are the points of concern. Further, the availability is only for limited period. Solar can be considered available during day time, subject to the variations due to cloud movements. Wind is seasonal in nature and in Indian conditions, the period of availability is only about 6 months.

From the above, the following conclusions can be derived.

- Nuclear generation to be considered as strictly base load factoring the planned maintenances

- Non schedulable hydro and renewable are to be considered as base load, but with periodicity as per historic availability and consistency. Only credible figures can be taken.

- Coal generation is to be considered as base load to the extent of about 55% of the unit rating of the expected units on grid, 55% to 80% of the unit rating with additional cost and the balance 15% fully as balancing power
- Schedulable hydro can be taken as balancing power, but subject to the probable availability as per storage availability forecast. Credible figures are to be taken and may be less than the unit rating of the machines on bar.

Demand side constraints

- Real time demand is to be met in any condition. This include any surge demand on account of festivals or any occasion having social attribute. The reduction in availability from the already contracted sources due to any technical issues are also to be factored depending on the probability of loss of generation from statistical figures.
- The demand pattern of the control area is quite important. If the control area is having more industrial load, the impact of weather is not very significant unless the weather conditions become so severe as to affect the normal living or movement of people.
- In a control area with major demand from domestic and commercial, as in the case of Kerala power system, even minor changes in the weather causes significant changes in the consumption pattern. Domestic load exhibits steep ramping during the evening dusk.
- The impact of commercial load is found to be almost similar to that of the domestic load, except the ramping down in the night hours.
- Agricultural load is seasonal, but it has the advantage of having maximum elasticity when appropriate price signals are given. In fact, this load can be used as filler for load balancing with appropriate tariff design itself.

The following conclusions can be derived

- The minimum demand can only considered for base load contracts. While determining the minimum demand, the border cases and outliers are to be excluded. In general, the minimum demand derived from the annualised average demand curve can be used.
- Seasonal demand can be considered as long term contracts from the sources exhibiting similar availability conditions. For example, a bilateral transaction between a South Indian utility and North Indian utility for the months of March to August is a typical case.

- Balance requirement has to be arranged through balancing market. Schedulable hydro and about 15% of the on-grid coal capacity can be considered by default available for balancing requirement.
- Spinning reserve and balancing non-spinning reserve are to be maintained for meeting the demand during any contingency.

Transmission constraints

- On the transmission side, the loading limits put constraints. These constraints may affect the scheduling of power on merit order.
- Typical conditions arise when the transmission system is insufficient
  - to import power to the control area due to which the low-cost import of power possible could not be utilised and instead high-cost power available within the control area has to be utilised. (This situation existed in Kerala)
  - to export power to other states where the low-cost generating station in the control area cannot export power to the market when the market rates are reasonably high. (Similar situation existed in Eastern Region of India in general)

Transmission constraints can be modelled as blinds in any standard optimisation packages and is dealt in the merit order package by providing market splits, by which the merit order software can intelligently assume modified figures.

8.3 DEVELOPMENT OF PORTFOLIO

The conventional approach in real time scheduling optimisation packages is to consider the variable cost of generation. This is so as the fixed costs for transmission and generation are already sunk costs. Here, we need to consider the fixed costs also, as the approach is also to optimise the contracts to be made by the utility for making power available for delivery within the control area. The algorithmic approach is given below.

Step 1: The total energy requirement for the control area for the control period of one year (E_{Tot}) is assessed through any standard forecasting tool. This is then split into sub-control periods, say monthly. In this thesis, monthly splitting is adopted.

$$E_{Tot} = \sum_{1}^{12} E(i) \tag{8.1}$$

where $E(i)$ is the energy requirement for each sub control period, given by

$$E(i) = E.n \tag{8.2}$$

where n is the number of days in the control period and E evaluated as per equation (3.2), which is reproduced below for ready reference.

$$E = 6.5\ MW_1 + 2\ MW_2 + 11\ MW_3 + 4.5\ MW_4 \qquad \text{(Equation 3.2)}$$

Step 2: The availability from each source is considered then without any scheduling restriction. This is done for each time period the requirement MW_i in equation (3.2) is worked out. The power balance equation given in (3.3) is then worked out, which is reproduced for ready reference.

$$MW_n = MW_{coal} + MW_{hydro} + MW_{Ren} + MW_{Others} + MW_{Bal}$$

From the matrix of MW, the MW_{Bal} for each time slot is obtained. The balancing energy requirement E_{BAL} is then worked out as

$$E_{Bal} = 6.5\ MW_{Bal\,1} + 2\ MW_{Bal\,2} + 11\ MW_{Bal\,3} + 4.5\ MW_{Bal\,4} \tag{8.4}$$

E_{Bal} can be positive if there is a need for purchase of power and negative if there is power available for sale.

Step 3: The surplus/ deficit condition, once identified on monthly basis, flexing of planned maintenance is thought of. The rate of power in the market on macro level is also assessed so as to facilitate "buy" during lower rate period and "sale" during higher rate period. After making such modifications, the energy demand supply balance is finalised.

Step 3: Integration of MW_{Bal} to E_{Bal} is not permitted for deciding sale or purchase quantity as netting of MW_{Bal} cannot be done. Flexing of variable generation to reduce the MW_{Bal} can be considered. This aspect goes into real time scheduling process and not attempted here.

Step 4: With the energy demand supply gap identified for consecutive years, the decision on whether sale or purchase is required is finalised. This also gives the total energy that has to be sold/ purchased in addition to the present contracts.

Step 4: The monthly requirement is then broken down into average daily conditions and the power demand for electricity for each time block is identified and balanced. The categorisation of hours adopted in the case study of Kerala is

Night off-peak- from 00:00 hrs to 05:30 hrs and 23:00 hrs to 24:00 hrs

Morning peak – from 05:30 hrs to 07:30 hrs

Day time – from 07:30 to 18:30 hrs

Evening peak – from 18:30 to 23:00 hrs

This analysis gives the exact requirement of power on average basis for each time slot. For finalising the purchase requirement, the base load is to be taken. In this process, the inherent limitations of generation systems with respect to variability need to be considered. During the minimum demand conditions, the generation portfolio may contain sources that have already touched the technical minimum and in such cases, surplus could exist. During high demand period, the generation from all sources if insufficient, may result in load restriction. This is illustrated in the case study in Table 8.3

Step 5: Having identified the deficit/ surplus, the market component is fixed. The cost of power from each source is considered and the overall cost is worked out. This cost is then minimised. Different market operation strategy (maintaining surplus during some period, imposing demand side management – value of lost load etc.) are considered and the appropriate portfolio is finalised.

Step 6: The deficit / surplus on annual basis is covered by long term agreements. The seasonal changes are covered through short-term contracts, settled either in cash at a predetermined rate or to be returned during some other period. The daily variations in demand are managed by very short-term market.

8.4 CASE STUDY – KERALA POWER SYSTEM

The case study is taken from Kerala Power System. Kerala Power System is dependent on import of power to almost 70% of its total requirement. About 30% internal generation is predominantly from hydro. The state has two stations running on naphtha, with very high variable cost of generation. As the details have commercial and strategic significance, the values have been moderated without affecting the purpose of demonstration of the method. The annual energy balance is given in Table 8.1

Table 8.1 Energy Balance Computation

Energy requirement MU	20000
Availability	
Hydro	7500
Nuclear	1000
Renewables	1000
Coal	9000
Others	500
Surplus (+)/ Deficit (-) (MU)	-1000

This indicates a deficit of 1000MU, which is to be purchased. This is repeated for the future years with the available projections as on hand. The typical details are given in Table 8.2. The details are worked out for 8 years here, which is the minimum required, considering the lead time for a generation project (other than renewables) to get commissioned.

Table 8.2 Energy Balance Planning

Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Energy requirement MU	20000	20800	21632	22497	23397	24333	25306	26319
Availability								
Hydro	7500	7500	7500	7500	7500	7600	7600	7600
Nuclear	1000	1000	1000	1000	1000	1000	1000	1000
Renewables	1000	1100	1150	1200	1300	1400	1500	1500
Coal	9000	9000	10000	10000	10000	12000	13500	13500
Others	500	500	500	500	500	500	500	500
Surplus (+)/ Deficit (-)	-1000	-1700	-1482	-2297	-3097	-1833	-1206	-2219

Justification of the figures considered

- The energy requirement for the base year was taken as a round figure of 20000MU. Afterwards, annual increase of 4% is assumed and worked out. In actual case, the values were based on the forecasting tool used in KSEBL.
- The hydro capacity is taken as 7500MU for 5 years and 100MU was added for the remaining period. Hydro capacity addition is possible only by

reservoir addition. This is a difficult task on account of the environmental issues. Modest increase was shown to show the difference.

- Nuclear capacity addition is also a very slow process. From the grid operating point of view, nuclear capacity addition is a real headache as it is not controllable and schedulable. As there are no major ongoing projects in South India as on date, no capacity addition is considered
- Renewable energy addition is very easy and is given all kinds of policy supports. Hence a uniform increase is given. However, the increasing penetration of renewables is bound to increase the generation costs and transmission costs though the cost of generation from renewable sources may come down per se.
- Power procurement from coal based stations on long term basis comes as packets as the generating stations are usually have 500MW or 660MW super thermal units.
- Others include micro generations, which is taken as a nominal figure. As the renewable generation is considered separately, no addition is expected in this category.

The energy and power requirement are to be further balanced. The power requirement for different time zones in a day is then considered which should add up to the energy requirement. Typical data is illustrated in Table 8.3. It can be seen that the deficit/ surplus is not uniform throughout the day.

Table 8.3 Typical Demand profile and Energy Balance

	Night off peak (MW)	Morning peak (MW)	Day (MW)	Evening peak (MW)	Annual energy forecasted (MU)	Annual Energy as per profile (MU)
No. of hours	6.5	2	11	4.5		
Requirement	1800	2400	2225	3150	20000	20129.75
Availability						
Nuclear	115	115	115	115	1000	1007.4
Renewable	100		400	100	1000	1003.75
Coal	1030	1030	1030	1030	9000	9022.8
Hydro	455	1205	640	1750	7500	7403.113
Others	100	50	40	40	500	500.05
Balance	0	0	0	-115	-1000	-1192.64

The cost of energy per unit is then optimised by minimising the cost function. The base case consists of the identification of different available sources (available on firm basis). The hydro is split into must-run and schedulable.

The schedulable hydro is provided as the balancing source in the base case. In the particular case, there is no surplus, but surplus condition may arise if the optimisation results in more availability than requirement. In this particular case study, the base case itself is almost at optimum, as the very high cost energy sources are already eliminated. Still further optimisation is possible. For finding this out, the average market rate is also given in the three different time zones. The details are then given in Table 8.4

Table 8.4 Power Procurement Cost Optimisation Base Case

	Night off peak (MW)	Morning peak (MW)	Day (MW)	Evening peak (MW)	Cost/unit
Nuclear	115	115	115	115	4.50
Renewable	100		400	100	5.00
Coal	1030	1030	1030	1030	3.90
Hydro must run	300	300	300	300	0.00
Hydro schedulable	155	905	340	1450	7.00
Others	100	50	40	40	4.00
Market Night off peak					3.00
Market Morning peak					6.00
Market Day					3.00
Market Evening peak				115	7.00
Total cost/ unit					4.2975

The constraints of generation and transmission system are applied on this base case and the optimisation program developed resulted in optimum case as given in Table 8.5. The optimisation is done by reducing the power from the sources which are controllable, viz. Coal based and Hydro. Nuclear, renewable and hydro must-run are not amenable to scheduling changes due to their characteristics.

The coal-based sources can reduce typically to about 85% of the capacity without much change in the cost of generation. This limit is however on the unit capacity and unit wise loading and the revision of schedule is to be worked out. This is done in the background program. The transmission capacity limits the import and export of power from the control area. In addition to the transmission capacity the reactive power requirement also put a limit on the minimum generation.

Table 8.5 Power Procurement cost Optimisation: Optimum Case

	Night off peak	Morning peak	Day	Evening peak	Cost/unit
Nuclear	115	115	115	115	4.50
Renewable	100		400	100	5.00
Coal	730	1030	730	1030	3.90
Hydro must run	300	300	300	300	0.00
Hydro schedulable	0	905	340	1450	7.00
Others	100	50	40	40	4.00
Market Night off peak	455				3.00
Market Morning peak		-500			6.00
Market Day			750		3.00
Market Evening peak				115	7.00
Total cost/ unit					4.0119

These aspects have been modelled as constraints by providing upper and lower range for import of power. The price of schedulable hydro is taken as the cost of generation of the highest cost generator likely to be used during the year.

From the Table 8.3 to 8.5, it can be seen that there is a reduction of 28.56ps per unit in the power procurement just by making use of hydro generation flexing with the market power.

8.5 PURCHASE DECISION

The total availability has to match with the total demand of the control area in real time in terms of MW and in the control period in terms of energy balance. The purchase decision then reduces to the simple task:

- Any positive difference in base demand and base availability to be met by long term contracts as the difference will only get diverged as the years progress. This can be counter checked by the positive difference in real time power as well as the annual energy balance.
- Any positive difference in the real time power availability and negative difference or lower difference in the energy balance for the control period refers to seasonal or diurnal shortage. This has to be met through short term power purchase. The identification of the time period requires further analysis, with the average figures replaced with monthly or daily figures as the case may be.

These are obtained from the results worked out earlier as per the steps detailed in chapter 6. The details are worked out for KSEBL for the period upto 2025 now.

8.6 OPERATION PLANNING ALGORITHM

The algorithm for ensuring economic operation of the power system in the above premises is derived. The steps are as follows:

(i) The first step involved is the modelling of the demand of the control area. The load-generation balance (LGB) is then prepared by considering the availability from all sources including thermal stations, the hydro generation and the power from open market (short-term).

(ii) The LGB is then prepared for sub – control period, usually a calendar month. At this stage, the typical conditions of the load are identified, subdividing a day into suitable number of time-blocks so that the demand remains almost flat during these time-blocks. In the case study of Kerala control area, the number of time blocks considered at this stage of optimisation was five.

(iii) As the first approximation, the entire marginal component for the peak shaving is assumed from the hydro. Having considered the requirement of hydro generation during peak, the assessment of the hydro available for daily generation other than peak is done. When the load generation balance is computed in this manner, the deficit or surplus condition is exposed.

(iv) The average cost of energy procurement is then worked out considering the market component for meeting the deficit or selling the surplus in the market with appropriate rates during each sub – period. The maximum rate in the market / any firm source as the case may be, is then finalised as the price of schedulable hydro.

(v) The shortage or surplus during each time bock is modified by varying the hydro generation during each period subject to the technical limits and obligations. With this modification, after say n iterations, the per unit cost of energy procured for the control period remains within a pre – specified band (for convergence). This gives the initial plan of operation.

(vi) At the operation stage, the swapping of hydro generation is considered with respect to the market prices on day – ahead and contingency market. That is, if the market price is lesser than a threshold price, the hydro generation is further reduced and water is conserved in the reservoir to the extent possible. It is pertinent to note that the base generation so determined need not be used on the same day in all cases. This depends on the depletion capability of the generating station attached to the reservoir and the rate of inflow into the reservoir. Thus, at this level, the computation requires the price of water in each reservoir during the time of operation and the safe reservoir level upto which conservation of hydro potential can be done.

8.7 HYDRO GENERATION PLANNING

The next task is to apportion the hydro generation among the different generating stations, especially those which are having no spill threat at a time. It can be seen that the reservoirs attached have different storage capacities and the generating stations have different depletion capabilities. This makes the spill threat at different times when generation is planned. The details of the reservoirs in Kerala are given in Table 8.6.

Table 8.6 Reservoir parameters

Reservoir	Full Reservoir storage in MU of the respective station	Maximum daily generation possible (MU)
Idamalayar	254.45	1.68
Idukki	2146.20	18.72
Kundala / Madupetty	79.57	0.77
Pamba/ Kakki	771.47	7.68
Sholayar	99.54	1.30
Anayirankal/ Ponmudi	45.46	0.77
Kuttiady/ Thariode	286.69	5.16
Poringal	10.62	1.25
Kallarkutty	2.28	1.85
Sengulam	1.28	1.15
Pambla	2.09	4.32
Kakkad	0.36	0.86

It can be seen that some of the reservoirs do not have the storage capacity even for a day's full generation. This indicates that these stations have high dependency on the rate of inflow for their normal operation and hence the chance of spill threat. Generally, these stations have the generation priced at the cost of generation during the period other than monsoon and Zero price during monsoon period (Must – run category). As the storage cannot be carried forward with considerable quantity the price during summer also cannot be the highest for the control period of one year as in the case of reservoirs with good storage, but a lesser period, say one to two days.

Another constraint in the application of price based algorithm for the scheduling of hydro generators is the water discharge commitment especially drinking summer for irrigation and drinking water requirements.

Based on these assumptions and the observations mentioned above, the procedure for determining the generation pattern from each generating station can be computed. The procedure indicated has factored the practical applicability in operating centres. The algorithm is given below.

Step 1: Assume the fixed numbers - carry forward at the end of control period (as on 31st May), actual storage at the beginning of the control period under study (as on 1st June), anticipated inflow month wise (from 10 year Moving Average), minimum generation requirement due to extraneous reasons (irrigation, drinking water commitments etc.), minimum generation requirement due to internal reasons like transmission constraints etc.

Step 2: With the minimum generation from June (as per Load Generation Balance requirement), work out the depletion required for avoiding spill threat. When generation is to be increased in any month on account of spill threat, recalculate from June again with the additional generation factored along with the minimum already worked out, apportioning the excess uniformly.

Step 3: After attaining initial convergence, check for the balance between load and generation. This requires the average LGB for each sub control period. Here the balancing is done on MW basis for the representative demand and availability for each sub period of the day. The MW availability from thermal stations is fixed first, followed by the hydro availability subject to the maximum generation possible from each station as per the computation arrived in step 3. The deficit / surplus are rearranged with consideration to the average price of power in the market. That is, in the case of surplus, maximum surplus will be made in the period when the market rate is high and maximum deficit will be made during the period when the market rate is expected to be low.

Step 4: The peak power requirement may necessitate thermal support on combined cycle, then the energy balance has to be checked again. Go to step 2

Step 5: The annual cost function is worked out at this level including the confirmed market power. To accommodate the hydro generation as per the minimisation requirement go to step 2.

8.8 IMPLEMENTATION OF ALGORITHM

The implementation of the above algorithm was done in Microsoft Excel using worksheet computations supported by VBA routines. For the purpose of computation, the volume of water in the reservoir is expressed in terms of the generation possible in MU (million kWh). In order to reduce the computation time, the details are to be collected from the usual daily statistics generated.

The monthly load generation balance (LGB) for the year is assumed in this exercise. The formulation of monthly LGB consider the availability from various sources and the corresponding price. The price of hydro is first assumed based on historical data and then modified as per the results obtained from this computation. The historical data is taken from the generation pattern of each station in the last ten years, normalised to the 10-year moving average annual inflow in the first iteration. The generation from downstream stations in cascaded schemes is related to the uppermost station and hence computed accordingly. However, where there is significant own inflow occurs to downstream reservoirs, the same is factored.

The results are displayed in excel sheet, which is linked to the computation of load generation balance of the control area. The sample sheet of computation pertaining to Idukki reservoir for the year 2015-16 is shown in Table 8.7. The computation is revised at least once every month and more frequently if there is significant difference in the assumed storage from the actual storage. The anticipated inflow assumed in the 0^{th} iteration is the expected inflow as per the 10-year moving average and this is also modified depending on the progress of monsoon.

Table 8.7 Storage Optimisation - Results

Reservoir: A Gen Station: A1 Computation as on 31-1-2017 - Iteration No.9							
FRL: 2146MU	Balance on May 31 : 341MU						
	Water available (MU)as on			Inflow Station (MU)		Generation possible/ Actual	Daily Gen possible/ Actual
	Month end Actual	1st day	Month end	Actual/ Anticipated	10year average		
June	388	448	388	229.33	323	289.58	9.65
July	780	388	779	590.25	618	198.99	6.42
August	1330	779	1330	701.72	472	150.715	4.86
September	1563	1330	1556	355.85	390	129.995	4.33
October	1646	1556	1640	294.39	256	210.655	6.8
November	1684	1640	1678	211.18	169	173.22	5.77
December	1589	1678	1583	54.19	55	149.57	4.82
January	1460	1583	1453	23.78	24	153.205	4.94
February		1453	1192	18.9	19	280	10
March		1192	833	31.11	31	390	12.58
April		833	574	40.9	41	300	10
May		574	**331.97**	67.86	68	310	10
			Total	**2619**	2465	2736	7.5
Computed Maximum Storage:			Monthly 78.19%			Daily: 87.56%	

The computation given in Table 8.7 is the output of 9th iteration done for reservoir A. This computation has considered the actual storage upto January 31st and pertains to the planning from February. The maximum storage on monthly is 78.19% and on daily basis, it has gone to 87.56%. The maximum storage occurred in November in this case.

Similar computation is repeated for other reservoirs. Each reservoir may have any number of iterations depending on the dynamics of inflow.

8.9 CONCLUSION

The management of the generation portfolio by adopting this method of computing the minimum generation to avoid spill threat was carried out from 2010. With the computations, it has been possible to build up the maximum storage without fear of spillage. The cost of power procurement was reduced.

CHAPTER 9

ANALYSIS AND INTERPRETATION

9.1 INTRODUCTION

The data for the works were taken from the Kerala power system. As the scholar was instrumental in managing the Kerala power system operation at that time, the observations made and the study results were applied and implemented step-by-step. Most of the details and numerical details furnished in this thesis are available in the public domain and are reproduced as such. The details are furnished in this chapter.

9.2 RECOMMENDATIONS EMERGED

The first observation was that there is a need to do detailed optimisation studies. The optimisation packages available in the market for power system operation planning are primarily focussing on profit maximisation of the utility, which can result in overall optimisation of the cost of power procurement. However, such optimisation was found to have local optima and it was observed that the cost of power procurement on annual basis could be reduced in some cases. Further, it was also seen that they can be used only with considerable customisation with respect to the peculiarities of Kerala Power System and also the regulatory framework available in India. Modifications with respect to the changes in the rules and regulations could not be implemented fully in these packages and some of them became obsolete. The process in Kerala followed the methods indicated in this work.

9.2.1 SWOC Analysis

After the SWOC analysis of Kerala power system and review of operation, mathematical model was developed. Based on the studies conducted, the following major recommendations emerged for minimising the cost of power delivered in the control area:

- The load factor is comparatively low for Kerala control area and the demand is vulnerable to weather conditions and social events on account of the peculiarity of consumer profile.
- Internal generation is insufficient to meet the demand of the control area and availability of inter-state transmission system is crucial in the management of the Kerala power system.
- The determination of power purchase requires more realistic forecast of peak power demand and energy demand. The forecast of energy requirement is found to be more realistic and methods to be developed for forecast of expected peak demand.
- The hydro generation capacity of the state is considerable with respect to the ramping requirements. The storage type reservoirs contribute about 40% of the hydro capability and shall be used for market based operation with sale when possible Hence, the scheduling of hydro generation should deviate from peak shaving principle and should align with merit order dispatch. There has to be procedure for hydro scheduling on merit order.
- The storage in the reservoir has to be maximised towards the end of the active monsoon period by appropriate optimisation mechanism.
- The thermal generation within the control area is very costly on account of the fuel utilised. This has to be addressed and to be phased out to reduce the cost of power procurement.
- The power purchase decisions are to be optimised so that the generation load factor does not deviate much from the demand load factor. The power availability from various sources, including the hydro potential, shall be classified as two categories only – schedulable generation and must-run generation. By applying merit order, the balancing power can be either positive or negative and accordingly short term purchase or sale has to be arranged. For long term contracts, optimisation has to be arrived at based on the base load determination.

Based on the above observations, the following recommendations emerged, implemented and the results are available now. The details are furnished below.

9.3 IMPLEMENTATION AND INTERPRETATION OF RESULTS

9.3.1 Long-term demand forecast

The deficiencies in the existing methods was overcome through a novel method combining statistical trend with load profiling for forecasting the maximum demand on long term basis. The method has given good results.

The forecast for the years from 2011-12 were verified with the actual figures. The details are tabulated in Table 9.1. The table contains both energy forecast and average peak demand forecast.

Table 9.1 Comparison of long-term demand forecast and the actuals for 6 years

Year	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
Forecasted consumption MU	19235	20400	20504	21536	23151	23501
Actual Consumption MU	19087	20053	20758	21734	22836	23819
% Error in energy forecast	0.78%	1.73%	-1.22%	-0.91%	1.38%	-1.34%
Computed average peak demand MW	2870	2985	3104	3228	3357	3491
Actual average peak demand MW	2856	2906	3035	3156	3295	3404
% Error in Peak Demand forecast	0.49%	2.72%	2.27%	2.28%	1.88%	2.56%

From the table, the % error in peak demand forecast is within 3%. Further, there are no negative errors. Evening peak demand projection is always made with positive error as otherwise it may lead to load shedding or power procurement at very high rates from real time markets. The results of the peak power forecast are very good in comparison with other methods.

9.3.2 Pricing of hydro generation

The procedure followed for scheduling hydro generation was based on peak shaving concept, generally based some rules of thumb formulated from statistical analysis and observations. In standard hydro – thermal coordination solutions, the daily generation limit of the hydro generation is either assumed or fixed. The existing process, though identified the utilisation of hydro power in periods of high usage, failed to reach the optimum scheduling. The availability of power in short-term market was not being fully explored and there is a growing need for shifting the operation strategy as the market was emerging. This issue was resolved by introducing the concept of pricing the hydro generation based on the determination of schedulable and must-run quantity of hydro generation.

The price of hydro generation for the schedulable portion from each generating station is arrived from the reservoir characteristics, expected inflow and current storage. Based on the above, the associated reservoirs can be classified as Group I, Group II and Group III. Group III stations are essentially run-off schemes. Group II stations are run-off for the active inflow period and Group I may be remaining in run – off condition for a short while during the peak of peak inflow period.

9.3.3 Storage optimisation

Merit order based hydro scheduling require storage optimisation for ensuring maximum availability of water for generation when the market price is high. Determination of spill threat and development of 70% - 10 days rule, significant improvement could be made in the storage towards the end of the active inflow period. Even in years with low rainfall, the storage achieved towards the end of the monsoon period could be maintained very high compared to the previous regime. This is evident from Fig. 9.1.

The storage optimisation not only supported the minimisation of cost of electricity within the control area, but also ensured sufficient water in the reservoirs for drinking water supply and irrigation during the summer.

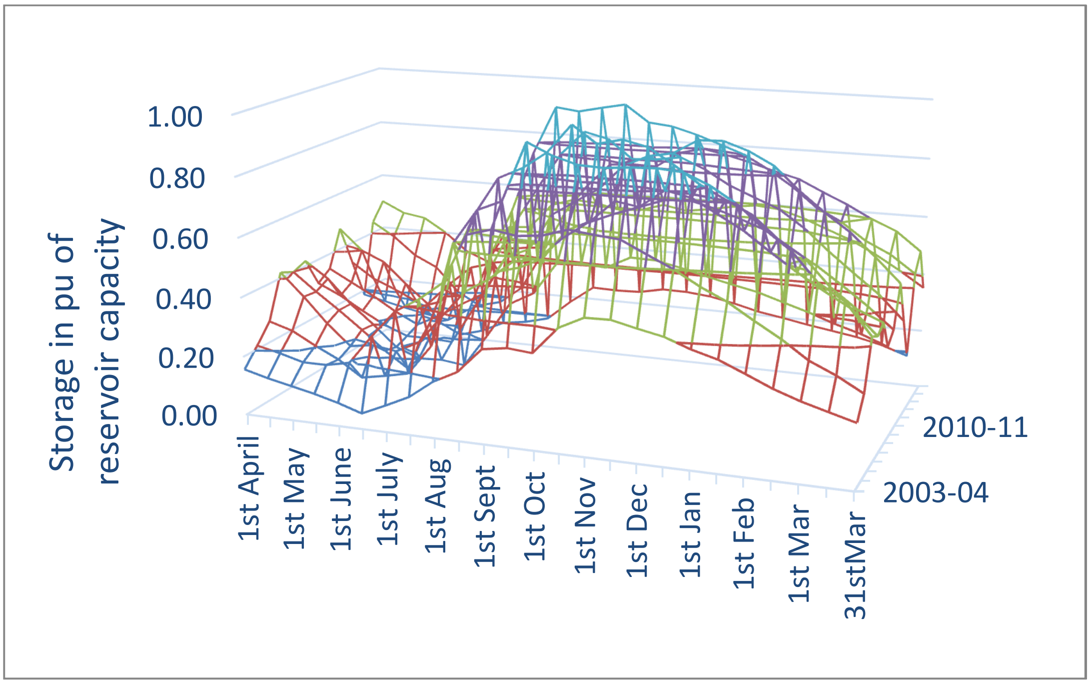

Fig. 9.1 Storage management Reservoir A 2003 to 2016

From the figure, it can be seen that there has been significant improvement in the storage in the reservoirs towards the end of active inflow period in spite of monsoon failures in some years.

9.3.4 Power Purchase Strategy – Portfolio development

Conventionally, the demand – availability balance in the state was carried out considering the available sources, which included high cost generation from internal thermal stations running on naphtha and LSHS. The introduction of open access of transmission system was utilised by the state to reduce the dependence on these high cost energy sources within the state. With the estimation of energy and peak power requirement more accurately as explained above, the confidence for entering into long-term power purchase agreements also improved and this was put into action. There had been issues in the implementation on account of the open access of transmission corridor allocation which delayed the implementation and was materialised progressively upto the desired level. The relevant figures taken from the Kerala State Electricity Regulatory Commission web site is tabulated in Table 9.2.

Table 9.2 Reduction of High Cost Energy: Energy in million units

Year	Consumption	Hydro	Naphtha sources	LSHS sources	Long term purchase	Short term purchase	CGS	Very short term purchases
2009-10	16726	6638	1969	746	0	0	7311	62
2010-11	17901	7145	1479	441	0	165	8096	575
2011-12	18420	8212	1003	354	0	536	8171	144
2012-13	19235	6947	622	225	0	1599	9650	192
2013-14	21390	6524	831	201	0	4482	9156	196
2014-15	21630	7065	218	244	0	940	9942	3221
2015-16	22680	6640	139	153	3225	1389	11042	920
2016-17	23955	4304	15	73	4231	3338	9734	2260
2017-18	25292	6474	0	0	5593	363	11000	1862

(Source: ARR and ERC of KSEBL downloaded from SERC web site)

It can be seen from the above table that the hydro generation is varying haphazardly across the years due to the variation in the inflow and the spatial distribution variations of the monsoon. The electricity demand is continually increasing and the energy from costly sources was successively reduced over the years. The electricity market was shallow in the beginning; the commissioning of major merchant generators started only 2012 onwards, about 6 years after promulgation of open access regulation in the present form.

From the table 9.2, it can be seen that the state was managing the demand with about 16% from naphtha based generation during 2009-10. The reduction of high cost energy and swap with low cost energy was one of the major recommendations made during the initial period of this study. The performance can be tabulated as in Table 9.3.

Table 9.3 Comparison of high-cost energy content in Kerala Demand

Year	Consumption in million units	High cost energy as % of consumption	High cost energy as % of sources other than hydro
2009-10	16726	16.23%	26.91%
2010-11	17901	10.73%	17.85%
2011-12	18420	7.37%	13.29%
2012-13	19235	4.40%	6.89%
2013-14	21390	4.82%	6.94%
2014-15	21630	2.14%	3.17%
2015-16	22680	1.29%	1.82%
2016-17	23955	0.37%	0.45%
2017-18	25292	0.00%	0.00%

(Source: ARR and ERC of KSEBL downloaded from SERC web site)

From the table, it can be seen that the % of high cost energy in the total energy mix was brought down successively from 16% to NIL in a period of 8 years. This gradual reduction was due to

- The procedural issues involved in obtaining transmission rights to bring power from other parts of India to Kerala.
- The strategic decision to split the requirement of power so as to avoid cartelisation and inflated bidding by the generating companies.

9.4 OPTIMISATION OF COST OF POWER PURCHASE

From Table 9.2 and 9.3, it can be seen that the short term and long-term purchase power purchase led to reduction in the electricity procured from high cost thermal stations within the control area. The generation from hydro sources is naturally limited by the inflow received during the year. The power procurement from central sector generating stations is on cost plus approach, meaning, the payment made is a regulated price where the regulator fixes the price on the basis of the actual cost of generation. The cost incurred for hydro generation is also on cost basis as it is internal to KSEBL. The sale of hydro power at higher prices gets compensated by the additional purchase at lower costs and as the net transaction is buy, it gets reflected in the price of power purchase. Hence, the comparison is on the expenditure incurred for purchase of power from naphtha sources, LSHS sources and purchase of power on long-term and short-term basis.

Table 9.4 Comparison of cost of power purchase from controllable sources Amount in Rs Million

Year	Naphtha	LSHS	Long term purchase	Short term purchase	Very short term purchase	Energy form these sources	Net rate
2009-10	18378.82	6210.08	0.00	0.00	279.00	2777	8.95
2010-11	13805.12	3671.11	0.00	734.40	2587.50	2660	7.82
2011-12	9362.09	2946.88	0.00	2385.68	648.00	2037	7.53
2012-13	5805.80	1873.01	0.00	7116.98	864.00	2638	5.94
2013-14	7756.63	1673.23	0.00	19948.91	882.00	5710	5.30
2014-15	2034.83	2031.18	0.00	4183.84	14494.50	4623	4.92
2015-16	1297.44	1273.65	12815.85	6182.29	414.45	4998	4.40
2016-17	140.01	608.02	16813.60	14857.08	10170.59	9917	4.29
2017-18	0.00	0.00	22226.06	1615.67	8380.49	7818	4.12

(Source: ARR and ERC of KSEBL downloaded from SERC web site)

From table 9.4, the weighted average rate for power from these sources was Rs.8.95 per unit during 2009-10. This got reduced to Rs.4.12 in 2017-18. Hence the implementation of the methods suggested as per this work resulted in a reduction of about 54% in cost. As the power hydro generation capacity is almost saturated, the reduction in the cost of power procurement is quite important as far as the control area is concerned.

9.5 CONCLUSION

The key observation is that the share of energy for meeting the demand within the control area from controllable sources was decreasing consistently during this period and has touched zero scheduling by 2017-18. The implementation of the recommendations as per the study was carried out progressively due to administrative and practical factors. The adoption of the recommendations as per this work has resulted in a reduction of about 54% in the cost of energy from controllable sources.

CHAPTER 10

SUMMARY AND CONCLUSIONS

10.1 INTRODUCTION

Availability of electricity at reasonable rate within the control area is important for the country and the state as much as the area distribution licensee for its commercial sustenance. This work has introduced some new concepts in the optimisation of power system operation from the point of view of minimising the cost of power procurement for distribution in a control area. The major contributions are summarised as follow:

- SWOC analysis of a power system with respect to the operational parameters to optimise the cost of power procurement for the control area on annual basis.
- Method to include hydro generation directly in the merit order dispatch principles instead of following rule curves
- Method to fix the must-run and schedulable portion of hydro generation using the reservoir parameters, inflow conditions and generation potential
- Method to conserve hydro generation so as to optimise the storage in the reservoirs
- Method to optimise the cost of electricity delivered in a control area on control period basis

10.2 UNIQUENESS

Several optimisation papers on power system operation optimisation have come in the research world. Many of these results have been used by the electricity industry. Hydro - thermal coordination, Optimum loading for loss minimisation, Optimum bidding strategy, Hydro generation coordination in cascaded schemes etc. have been attempted umpteen. However, such individual solutions had the issues of convergence to local optima. Optimisation of generation by the individual generating companies or optimisation on transmission losses etc. need not result in minimisation of cost of electricity distributed in a control area. The procurement plan as well as consumption pattern of electricity has annual characteristics. Hence the optimisation of cost of electricity delivered in a control area is to be considered on annual basis also. In addition, a long-term procurement plan is also to be taken by the distribution licensee, for meeting the bulk of the demand. In this work, effort is taken for moving from local optimisation to global optimisation where the interest of all stake holders in the control area is protected optimally without compromising on minimisation of price of electricity delivered in a control area. Thus, this work is unique.

10.3 IMPLICATIONS

The implications of the work carried out can be summarised as follows

- Implications on the transmission system development

  The possible cost reduction by transmission system augmentation instead of adding generation capability within the Kerala state was established and steps were taken.

- Implications on the power availability in the state

  With the improved provision for power import, the need for load shedding and power cut could be eliminated during contingencies of any generator outage by increasing power purchase.

- Implications on optimisation

  The hydro scheduling was separated from the conventional peak shaving method and was included in merit order dispatch.

10.4 CONTRIBUTIONS TO VARIOUS STAKE HOLDERS

10.4.1 Contributions to Academic World

This study is based on the present situation existing in India and the ways and means to improve the performance parameters of grid management. This work has put emphasis on the global optimisation, viz. minimisation of cost of electricity delivered in the control area. The control area has been delimited to the political boundaries of the states in Indian context at present.

The concept of SWOC analysis of the power system and evaluation of the constraints is developed in this work. No work could be traced to identify the parameters required for SWOC analysis of a power system for minimising the cost of electricity delivered in the control area. The attempt has given insights into the action plan to arrive at the solution.

The concept of determining price for hydro generation and determination of spill threat has been evolved in this work, by which the hydro scheduling perfectly fits into the merit order scheduling and real time cost optimisation is taken care of. The methods developed replaced the conventional rule-based judgement in hydro management with more transparent and scientific method.

10.4.2 Contributions to Distribution Licensees

The thesis has developed practically feasible methods to assess the various aspects involved in the overall optimisation of operation. Stress has been put on the ease of computation at operational level and the acceptability of the computation and interim results at top management level. Specifically, tools requiring special knowledge of mathematical modelling, ANN etc. have been avoided. The observations from the statistical analysis have been put into use to develop some relations in the portfolio decision making for operation.

The conventional power system management is to find the resources to meet the requirement within the control area by means of generation. The concept of market-based load-generation balance has just evolved in India. The economy of meeting the requirement of energy at the consumption point is in the form of electricity. Development of method for assessment of peak requirement from energy forecast and the load profile determination has given good results than the econometric and other methods in vogue. This method is novel and unique.

The major contribution in this work is the implementation of models which are easy to use and palpable to managers working in the power system operation for optimisation on annual basis of the cost of power procured for delivery in the control area.

This work is based on the field requirement in the optimum operation of the power system. Tedious and involved methods of optimisation have been replaced with simple logic which can be implemented in Microsoft Excel, by which modifications depending on the changes in technology and regulations can be implemented easily.

10.4.3 Contributions to Regulators

In the Indian context the regulators have to monitor the performance of the utilities whose tariff is administered by them. The absence of a mechanism to ensure global optimisation in the operation of the power system with respect to the control area may lead to local optimisation and affect the cost of power delivered in the control area. The tools developed in this thesis are sufficient to fill this gap.

10.4.4 Contributions to Government

The benefits to the government are from the part of planning the new investments in the power sector and to formulate necessary policy framework to obtain the desired results. The efficient method to obtain long-term demand forecast is useful to the extent that the investment in the development of infrastructure is optimised. For example, the results can be used in determining the optimal capacity of nuclear power, wind power, solar power etc. and the requirement of balancing power from hydro, need for pumped storage, other storage systems etc. Such optimisation could result in avoiding over construction and ensuring proper utilisation of resources.

10.4.5 Contributions to Consumers

The consumers are basically benefitted by the reduction in the cost of electricity. In the study case presented, it was shown that there is a reduction of about 54% in the expenditure towards the cost of energy from controllable sources. This reduction has helped in containing the price of energy delivered in the control area to a large extent. These are evident from the tariff determination done by Kerala State Electricity Regulatory Commission.

10.5 LIMITATIONS

The methods developed are applicable universally. However, the models need to be modified respect to the power system which is to be studied for optimisation. The major changes include the characteristics of the rainy period, changes in the consumer profile and the consumption pattern etc.

Renewable energy has been taken as must-run in this work. However, as the penetration of renewables increase, the ramping effect due to uncontrolled RE penetration and the backing down of RE sources become necessary and is to be included in the model similar to the hydro.

10.6 SCOPE FOR FURTHER WORK

The work has not considered the management of renewable energy when the penetration goes high. The behind the meter generation from renewables, which is expected in large quantity has the effect of apparent reduction in the demand for electricity. The impact study is reserved for future works. However, such issues could affect only the load curve and the methodology for optimisation of other modules in the thesis remains unaltered.

The optimization of renewable penetration and development of appropriate level of storage mechanisms vis-à-vis cross-country transmission system development with appropriate compensation mechanisms has not been considered here. The matter is bound for changes in technology in immediate future. The battery costs on the down trend may influence the decision on pumped storage schemes and the development of transmission schemes even. This is reserved for future studies.

The role of hydro generation potential especially from those associated with large reservoirs could see better opportunity in the balancing market. The present energy market in India is not fully equipped to handle the balancing market requirements. Equally important if the scope for the tertiary control market, which is a necessity for maintaining the frequency and voltage within limits as the present ABT mechanism has lost the sheen on account of frequency stabilisation. The balancing market mechanism to take care of optimum utilisation of the underlying assets is not considered in this work. This is a separate matter and reserved for future works.

The development of market for renewable energy including storage, electric vehicle deployment, smart metering system etc. are taking shape in different parts of the world in different dimensions. The electric vehicle charging could provide a buffer storage in the grid if provided incentive. This is also reserved for future studies.

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APPENDIX

SAMPLE OUTPUT SHEETS FROM EXCEL

Project	Idukki	Period	Jun-15	May-16	Conversion constants	Gross	1.51	Station	1.47		
Reservoir	Idukki										
FRL	2146	MU	Carry forward at the end of water year			341.25	MU				
	Storage (Station MU)			Inflow Stn MU		Generation					
	Month end Actual	1st Computed	Month end Planned	Actual/ Anticipated	10year average	Monthly possible/ Actual	Daily possible / Actual	MW Availability	10 year average Inflow Gross	Anticipated inflow Gross	Actual inflow Gross
June	949	728.38	951	373.63	294.54	150.665	5.02	630	302.56	383.80	383.7993
July	1155	951.35	1155	406.26	638.31	203.1	6.55	630	655.68	417.31	417.3109
August	1199	1154.50	1197	260.52	485.91	218.44	7.05	630	499.13	499.13	267.6055
September	1170	1196.58	1166	205.00	406.36	235.465	7.85	630	417.42	417.42	210.5809
October	1192	1166.12	1187	216.00	259.04	194.62	6.28	630	266.09	266.09	221.8808
November	1252	1187.50	1246	173.33	178.80	114.765	3.83	630	183.67	183.67	178.0447
December		1246.06	1174	57.70	57.70	130	4.19	630	59.27	59.27	
January		1173.76	1048	23.83	23.83	150	4.84	720	24.48	24.48	
February		1047.60	916	18.33	18.33	150	5.36	720	18.83	18.83	
March		915.92	626	30.36	30.36	320	10.32	720	31.18	31.18	
April		626.28	475	48.73	48.73	200	6.67	720	50.05	50.05	
May		475.01	341.25	66.24	66.24	200	6.45	720	68.05	68.05	
				1879.93	2508.15	2267.055			2576.40	2419.28	

Project	SBGR	Period	Jun-15	May-16	Conversion constants	Gross	1.918	Station	1.615		
Reservoir		Pamba, Kakki interconnected permanently									
FRL	771.47	MU	Carry forward at the end of water year			83.99	MU				
	Storage (Station MU)			Inflow Stn MU		Generation		MW			
	Month end Actual	1st Computed	Month end Planned	Actual/Anticipated	10year average	Monthly possible/Actual	Daily possible/ Actual	Availability	10 year average Inflow Gross	Anticipated inflow Gross	Actual inflow Gross
June	243	162.13	244	178.84	130.11	97.347	3.24	275	154.52	212.39	212.3938
July	312	243.62	313	177.98	304.29	108.593	3.50	275	361.38	211.37	211.3702
August	344	313.01	345	152.45	225.12	120.9355	3.90	270	267.36	267.36	181.0486
September	353	344.52	354	94.74	205.48	85.7225	2.86	270	244.03	244.03	112.5147
October	398	353.54	399	117.70	156.43	72.275	2.33	275	185.77	185.77	139.7828
November	519	398.96	520	162.77	128.66	42.123	1.40	270	152.79	152.79	193.3062
December		519.61	514	64.22	64.22	70	2.26	275	76.27	76.27	
January		513.83	482	33.28	33.28	65	2.10	320	39.52	39.52	
February		482.11	425	23.27	23.27	80	2.86	320	27.63	27.63	
March		425.38	300	34.60	34.60	160	5.16	320	41.10	41.10	
April		299.98	194	34.07	34.07	140	4.67	320	40.47	40.47	
May		194.06	83.99	29.93	29.93	140	4.52	320	35.55	35.55	
				1103.86	1369.46	1181.996			1626.39	1534.26	

LIST OF PAPERS
SUBMITTED ON THE BASIS OF THIS THESIS

1. **Anand S R, Dr. C.A. Babu** and **Dr. V.P. Jagathyraj** (2016) A practical approach to assessment of the base power contracts and peak power contracts for a distribution utility. *Electrical Power and Energy Systems* 78 (2016) 385–389. www.elsevier.com/locate/ijepes

2. **Anand S R, Dr. C.A. Babu** and **Dr. V.P. Jagathyraj** (2018) A Practical approach to Storage Optimisation and Hydro Scheduling in mixed market environment for distribution utility owned generation stations. *IOSR Journal of Engineering* (IOSRJEN), ISSN (e): 2250-3021, ISSN (p): 2278-8719, Vol. 08, Issue 7 (July. 2018), ||V (II) || PP 58-65. Accepted for Renewable Energy World Conference, New Delhi, May 17-19, 2017, www.renewableenregyworldindia.com

3. **P.G. Latha, Anand S R** and **T.P.Imthias Ahamed** (2011) Improvement of Demand Response using Mixed Pumped Storage Hydro Plant. *IEEE PES Innovative Smart Grid Technologies – India*

4. **P.G.Latha, Anand S R, Imthias Ahamed** and **G.Madhu** (2011) A Different Approach on Pumped Storage Scheduling. *4th National Conference on Advances in Energy Conversion Technologies* (AECT 2011), Feb 03-05, 2011

5. **K. Pramelakumari, Anand S R, V. P. Jagathy Raj** and **E. A. Jasmin** (2012) Short-term load forecast of a low load factor power system for optimization of merit order dispatch using adaptive learning algorithm. *International Conference on Power, Signals, Controls and Computation, IEEE*

6. **Anand S R** (2014) Renewable Energy Integration – Challenges, Limits and Mitigation. *1st Sustainable Development Congress* (SuDCON) 2014, December 13-14, Kottayam.

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Employment history

Guardian Controls, Thodupuzha	1988
Hindstan Paper Corporation	1988 – 1989
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Others

1. Guest Faculty at Power Engineers Training and Research Centre, Moolamattom on Power System Operation
2. Best System Operator 2015 in India awarded to Kerala by Central Board of Irrigation and Power during my tenure