5. HYDROTHERMAL OPERATION

5.1 INTRODUCTION

The importance of operation planning increases according to the installed capacity of interconnected systems. It becomes a necessity when the aim is to achieve the optimum utilization of available resources according to the needs of the users.

The complexity of the problem has increased in recent years with the privatization of the power sector in various countries. The search for optimum solutions has acquired new dimensions. Frequently, the contractual conditions have imposed new restrictions, which need to be observed to avoid the payment of claims due to violations of agreements by the power utilities.

On the other hand, the trend towards interconnection of power systems (power pooling) has also introduced new aspects to consider. In order to be able to supply power at low cost to the consumers, through interconnections the power utilities expect to export energy at a high price and to import at a lower price. With these targets in mind, power utilities in industrialized countries are relying on strategic planning.

5.2 BASIC DATA

For a rational system management, reliable data is required at the right time. The basic data comprises mainly:

- System loads (total system and/or independent load centers)
- Hydrologic and meteorological records
- Water requirements for different uses (drinking water, irrigation etc.)
- System characteristics (generation and transmission)

SYSTEM LOADS

This information is normally available in dispatch centers. It is always desirable to have the maximum volume of information of loads including system losses. Estimation of system load on basis of the historical generation does not necessarily reflect the system demand, especially when deficit exists.

The data is processed and synthesized to facilitate its analysis and use by different application programs. For example, peak loads, minimum load and energy, for daily, weekly, 10-daily and yearly periods are established.

HYDROLOGY AND METEOROLOGY

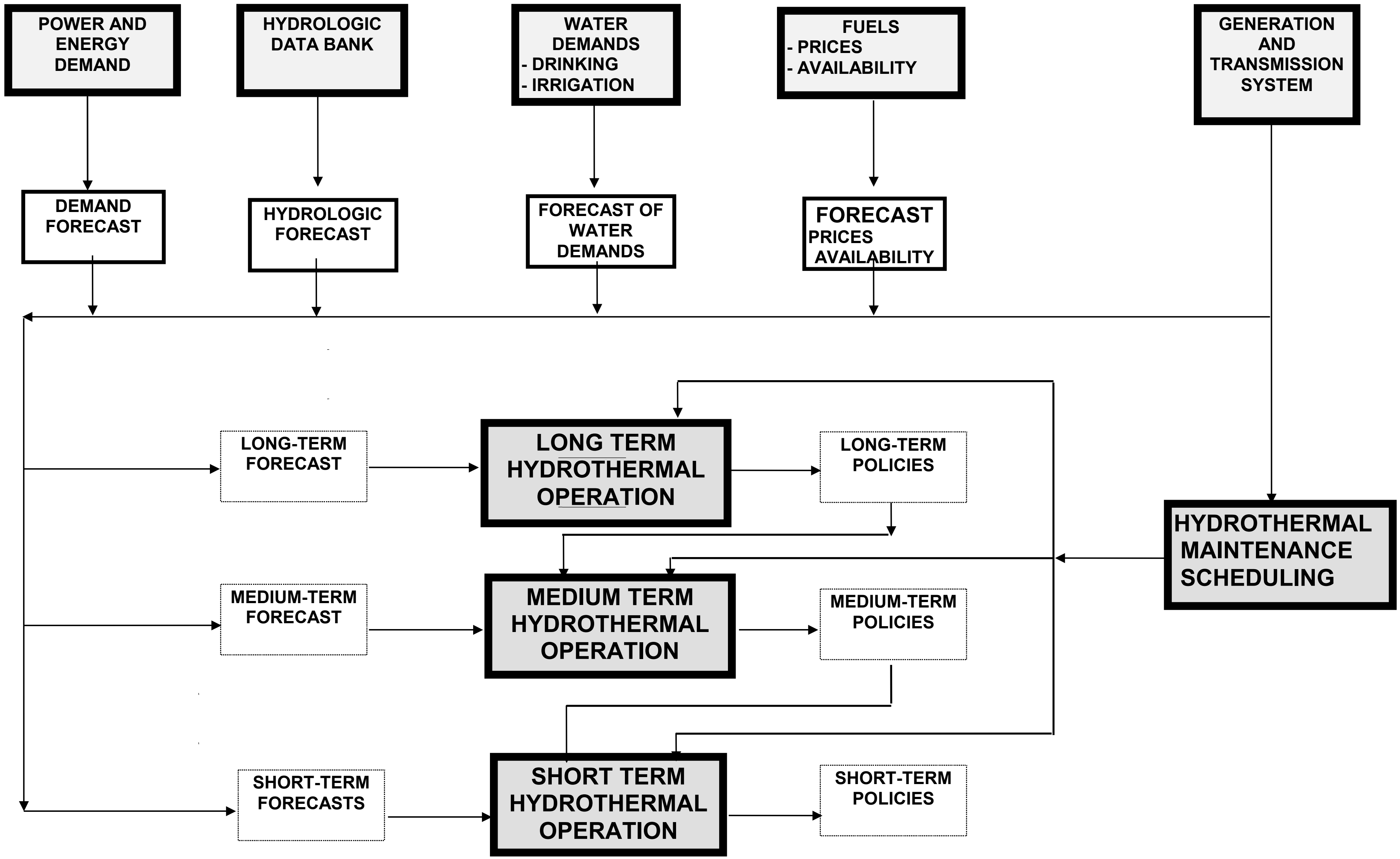
This is indispensable information in case of hydrothermal systems. The data can be processed and stored with help of suitable software packages such as DBHYDRO

The hydrologic data provides the basis for the forecasting of natural flows. The meteorological data may be used for stream flow forecasting, as well as for forecasting of system loads when these are affected by climatic conditions.

FUELS

The fluctuations in prices depend on local and international factors. However, it is very important to establish and consider their availability in time and space.

GENERAL STRUCTURE OF COMPUTERIZED SYSTEM FOR OPERATION PLANNING



SYSTEM DATA
Comprises the information about the characteristics of the different elements, which constitute the interconnected system. The data includes: the characteristics of

- Hydroelectric plants (reservoirs, generating units, etc.)
- Thermoelectric plants (boilers, generating units, etc.)
- Transmission system (lines, substations, etc.)

5.3 FORECASTS
These are required according to the different planning horizons. These must be available according to the adopted time discretization. Generally:

- Annual or multi-annual with monthly, 10-daily or weekly discretization.
- Monthly, 10-daily or weekly with daily discretization
- Daily with hourly discretization.

Various algorithms are available to allow the selection of the most suitable ones in accordance to data availability. These include;

- Time series analysis (spectral analysis, autoregressive models, ARMA models, disaggregation, filtering, etc.)

- Multiple linear and non-linear regression

5.3.1 SYSTEM LOADS
5.3.1.1 LONG TERM POWER SYSTEM DEMAND
The demand forecasts are required for all considered planning horizons. These should comprise growth pattern, seasonal, weekly and daily fluctuations. The system losses may be included as part of the forecast. Alternatively, the system losses can be an optimization parameter to be accounted for in the unit commitment and economic dispatch.

A procedure based strictly on the analysis of historical loads could be as follows:

- Annual peak loads are determined according to the annual growth rates
- Monthly peak loads are calculated on basis of monthly factors
- Monthly energy requirements are determined based on the monthly load factors
- Annual energy requirements are calculated adding the monthly values
- Block loads, in terms of power and energy, are added if applicable

Total power and energy demand, both monthly and annually, are determined by adding the corresponding monthly values of each subsystem according to the interconnection dates.

5.3.1.2 SHORT TERM LOAD FORECASTING
There is a wide variety of models for short term load forecasting. The type and structure of the model applied depend on the characteristics of the load. Of special importance is the consideration of weather dependence of the load.

Following components need to be identified in the time series:

a) Periodicity (seasonal, weekly, etc)
b) Growth
c) Randomness

Before each component is removed, the correlogram of the time series may need to be calculated with the formula:

$$r_k = \frac{\sum_{i=1}^{n-k} x_i x_{i-k} - \frac{1}{n-k}\sum_{i=1}^{n-k} x_i \sum_{i=k-1}^{n} x_i}{\sqrt{\sum_{i=1}^{n-k} x_i^2 - \frac{1}{n-k}\left[\sum_{i=1}^{n-k} x_i\right]^2}\sqrt{\sum_{i=k+1}^{n} x_i^2 - \frac{1}{n-k}\left[\sum_{i=k+1}^{n} x_i\right]^2}}$$

Where,

r_k = autocorrelation coefficient of k^{th} order
X_i = element of time series
n = number of elements in the time series
k = lag between two elements of the time series
Confidence at 95% confidence limit are established as follows:

$$\frac{-1.96}{\sqrt{n}} \leq r_k \leq \frac{1.96}{\sqrt{n}}$$

PERIODICITY
The correlogram of a time series with a strong cyclic component will have a shape as shown in Fig. 5-1. Ciclicity is removed in this program through the analysis of daily peak loads and is achieved through subtraction of average peak values for the period under consideration.

The transformed series X'_t is calculated as:

$$x'_t = x_t - \bar{x}_d$$

Where,

X_t = Original time series
X'_t = modified time series
X_d = Average load for weekday d

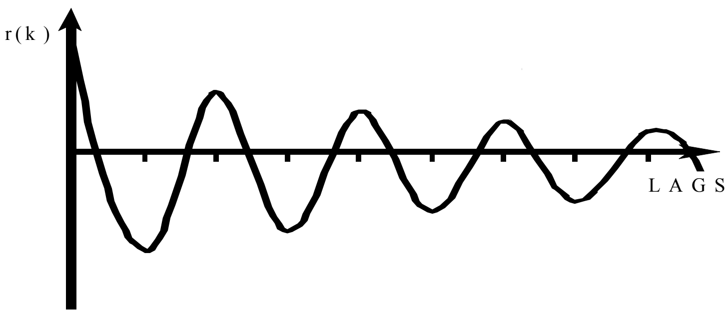


Fig. 5.1: Correlogram of Series with Cyclic Component

TREND

The existence of a trend in the time series can be intuitively identified. However, this should also be accomplished mathematically. The correlogram of a time series with a trend component has a shape as schematically shown in Fig. 5-2. The growth component is removed by taking the first difference of the time series. This achieved by applying the equation:

$$x''_{t,t+1} = x'_{t+1} - x'_t$$

Where,

$X''_{t,t+1}$ = resultant value of taking difference between 2 consecutive values (t,t+1)

X'_t, X'_{t+1} = Previously modified time series

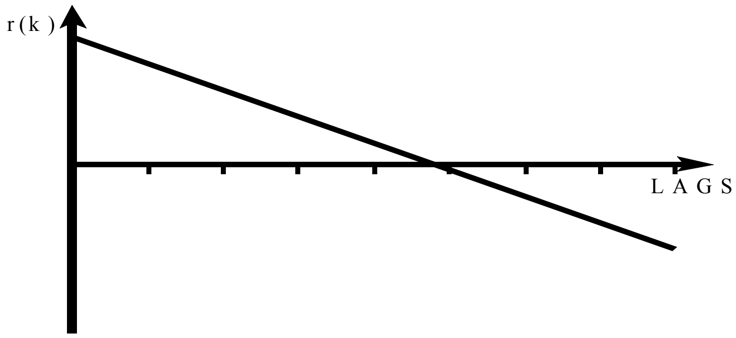


Fig. 5.2: Correlogram of series with trend component

RANDOMNESS

The resulting time series is also analysed with help of the correlogram. If the time series is random, the correlogram will most likely have a shape as schematically shown in Fig. 5-3.

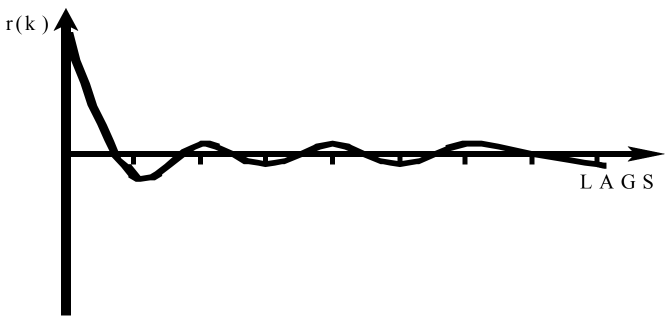


Fig. 5.3: Correlogram of random series

An empirical frequency distribution is fitted to the residuals resulting from the first difference. This allows the straightforward generation of residuals with help of standard random number generators. Details are given below.

HOURLY UNIT LOADS

The analysis of hourly unit loads is carried out for each weekday and hour separately. The statistical analysis basically comprises the determination of frequency distributions of all p.u. values subdivided in 24 hours/day and 7 days/week. Therefore a total of 168 distributions are calculated. Additionally, basic statistical parameters, such as mean and standard deviation are also calculated. No analysis is made to determine wether the daily and hourly values are serially correlated.

Extremely low values, with a limit internally fixed in the program at 30%, are eliminated through a filtering process. This is to avoid the distortion of the basic statistical parameters by occurrence of load shedding or disturbance in the system.

FORECASTED LOADS

The forecasted daily peak loads for every weekday are determined following a reverse procedure, according to following steps:

a) Generation of random values on basis of the empirical distribution of the residuals of first difference.

b) Calculation of trend according to following equation:

The term $X''_{t,t+1}$ is randomly generated at every time step on basis of the empirical distribution of residuals.

From previous equation, the term X'_t will be known at every time step. However, an initial value is determined form the recorded time series for t=0.

c) The forecasted peak daily loads are estimated according to the equation:

The hourly p.u. loads are estimated randomly on basis of the empirical distributions of hourly p.u. values. As already mentioned, a total of 168 hourly distributions are used, corresponding to 24 hours/day and 7 days/week.

The absolute (MW) hourly loads are calculated by multiplying the p.u. hourly values and the forecasted daily peak loads.

The following figure shows a comparison of measured and estimated peak loads and daily energies determined on basis of mean daily temperatures measured in different cities of Pakistan, namely Islamabad, Lahore, Peshawar, Faisalabad and Multan.

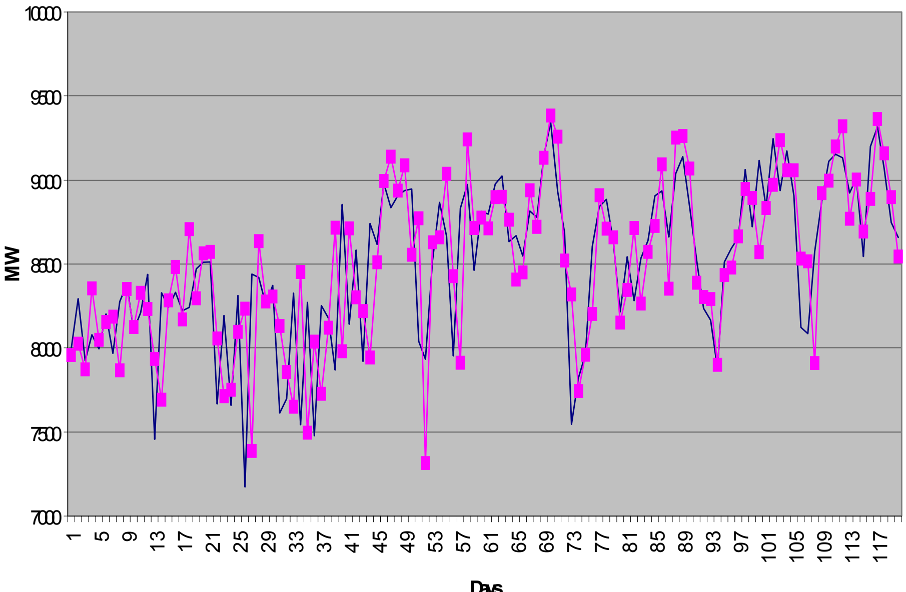


Fig. 5.4: Peak load as function of mean daily temperature at Islamabad, Lahore, Peshawar, Faisalabad, and Multan

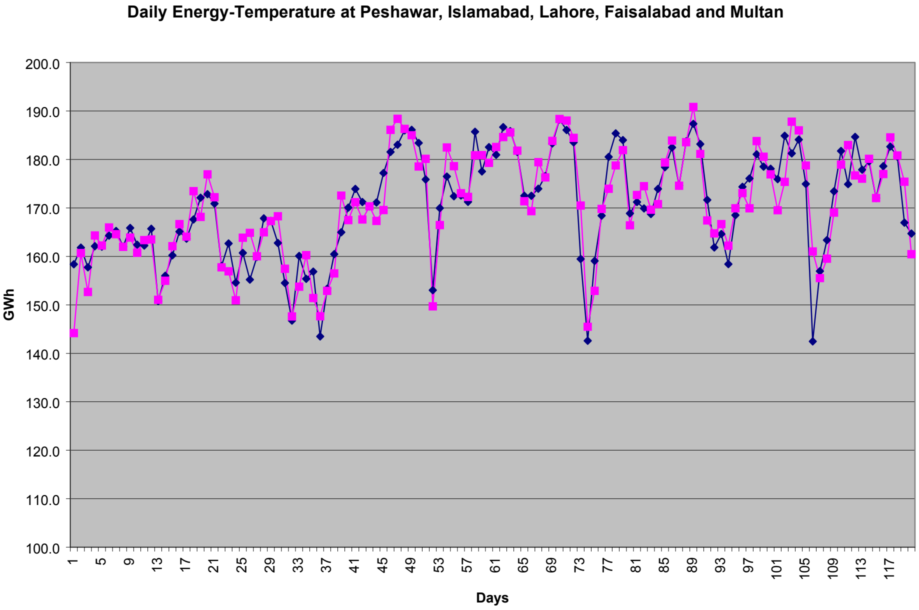


Fig. 5.5: Daily energy as function of mean daily temperature at Islamabad, Lahore, Peshawar, Faisalabad, and Multan

5.3.2 WATER DEMANDS

Water demand and water management may have to be considered as part of the requirements for drinking water, irrigation, flood control and other uses. The magnitude and importance of the water requirements vary according to system characteristics, hydro climatic conditions, etc. The information is required to correctly establish the value of water, especially when conflicts exist in the use of water for human consumption, irrigation, power generation, etc.

On the other hand, a special case of water requirements also exists when the thermal units are used for desalination of seawater to supply drinking water.

5.3.3 HYDROLOGY

Hydrologic forecasts must be prepared according to the different planning horizons considered. The reliability of the forecasts will depend on the quality and quantity of available hydro-meteorological data.

5.3.3.1 MEDIUM/LONG TERM STREAMFLOW FORECASTING

The methodology for forecasting river flows is based on decomposition of the time series of recorded values. The series is separated into deterministic and stochastic components.

The deterministic part is determined through spectral analysis and the residuals with a disaggregation model.

TIME SERIES ANALYSIS

The extraction of information from time series is known as time series analysis. When applied to natural processes, time-series analyses often yield information that provide an insight to cause-and-effect relationships influencing the parameter of concern. The techniques can be used to establish recursion relationships that have application in the synthesis of predicted time series.

Through time series analysis, following main components are sequentially established:

- Trend
- Frequency
- Randomness

The components are removed sequentially. Removal of the trend leaves the frequency and randomness; the removal of the frequency leaves only the random component.

The variance σ^2 is a key parameter in time-series analysis. This statistic parameter is an indication of the variability of the data in the record. All above-mentioned components contribute to the total variance of the time series:

$$\sigma^2 = \sigma_T^2 + \sigma_F^2 + \sigma_R^2$$

The variance contributed by each component can be isolated. The random component will be truly random only when all frequency components have been removed.

Most time-series describing natural processes are serially correlated, meaning that preceding and succeeding events are correlated. This is the case of periods of high and low flows.

A measure of the correlation is given by the auto covariance function:

$$R(\tau) = \sum_{i=1}^{n-\tau}(x_i - \mu_x)(x_{i+\tau})/(n-\tau)$$

x_i, $x_{i+\tau}$: dependent variables at times i and i+τ, respectively
τ : time lags, τ = 0, 1, 2, ..., m

It is often convenient to normalize the auto covariance function $R(\tau)$ by the auto covariance of the time series, which in fact corresponds to the auto covariance with time lag τ = 0, R(0). The resulting function is known as the *normalized autocorrelation function* $R(\tau)_0$, having a value of 1.0 at τ = 0.

This function also provides information about persistency in the time series under consideration.

- When the function remains positive, then persistence exists. High flows are followed by high flows and low flows are followed by low flows.
- A negative function will indicate also that persistence exists. However, high lows will be followed by low flows and vice versa.
- $R(\tau) = 0$ is an indication of lack of persistence.

A plot of the normalized auto correlation function against the time lags is known as *correlogram.* An example is given in Figure 3-1.

SPECTRAL ANALYSIS
The auto-covariance function is useful also for the development of the *variance spectrum* or *power spectrum.* The analysis through the power spectrum may help in establishing periodicities in the time series, which are not so evident.

Any random component present in a record may be concentrated in certain frequency bands of the record's spectrum. The variance spectrum at frequency 0 includes all the record variance, which does not reoccur in the period of analysis. Therefore, the spectrum at frequency includes:

1. Any linear trends in the record

2. Any periodic components in the record of such low frequencies that they appear as linear models
3. Any random component with a variance of frequency

The Fourier transformation of the auto-covariance function from the time domain to the frequency domain is used in the development of the power spectrum. The variance spectrum is formed by plotting the values of the spectral estimates against the corresponding time lags. An example is given in Figure 3-2.

The fundamental frequency is given by $\omega_r = \pi w/lags$

The fundamental period fp = 2 * lags/w

Following basic recommendations apply:

- The optimum number of lags is approximately 10% of the total number of records.
- The length of record analyzed should be at least 10 times as long as the longest significant period.

DESAGGREGATION
The main purpose of desegregation models is to preserve historical statistics at more than one level, In general, the parameters to be preserved are the same as those in the classical auto-regressive models. The distributions are preserved through transformations and standardizations made before modeling. The model itself is used to preserve variances and to preserve linear relationships between variables and covariances.

For the residuals, the model used is of the form (Valencia and Schaake, 1973):

$$Y = AX + B\varepsilon$$

where:

Y	= column vector of seasonal values
X	= annual series
ε	= random component
A, B	= matrices of parameters

5.4 MAINTENANCE SCHEDULING
This is a fundamental activity which becomes more important with the involvement of privately owned generating plants and the interconnection with other systems and/or countries. Must include economic and reliability aspects. Operation planning is only possible when the availability of the generating units is known. Maintenance scheduling allows to:

- Define the dates when the units have to undergo preventive and corrective maintenance.
- Coordinate the generation of private generating plants
- Fix the periods and conditions to import/export energy
- Achieve minimum operational costs for the whole system
- Ensure minimum acceptable reliability levels

The optimization can be made with algorithms based on heuristic methods and/or algorithms based on mathematical programming techniques.

5.4.1 INTRODUCTION

The developments in recent years have been characterized by a continuous growth of electricity demand with an increased concern about the environmental impact of power generation. One important consequence of this has been an increase in the cost of electricity.

A very important activity in system operation is the scheduling of the maintenance of the generating system. The purpose is the coordination of the yearly maintenance of the units. The objective is the minimization of yearly operation costs subject to operational constraints as well as manpower requirements, remodeling/refurbishing plans, etc. A critical consideration is the compliance with minimum system reliability.

Presently, in most power utilities the maintenance scheduling is manually prepared, in some cases with the help of simple heuristic models. HTMS is computer based procedure based on mathematical programming techniques which aims at the determination of optimal maintenance strategies though the minimization of production costs keeping in view the reliability of operation.

5.4.2 BACKGROUND INFORMATION

5.4.2.1 OPERATION PLANNING

Due to the new trends towards liberalization of markets and the privatization of power sector, the market has become highly competitive. The power utilities require to further improve the performance of their systems through an efficient expansion and operation of their interconnected systems.

Tools are available to establish **optimum expansion strategies** for the generation system keeping in view reliability levels as well as investment and operation costs. The aim of these activities is to establish the required additions to the system, their size and commissioning time. These planning efforts are carried out considering planning horizons which can cover various decades.

The other important field is the **optimum operation planning** of interconnected systems. This considers the optimum utilization of available infrastructure, without addition of new units. Depending on the system characteristics, the planning horizon covers one year. This is especially the case of hydrothermal systems, where the output of the hydropower plants depends on the cyclic availability of water inflows.

The types of models being adopted depend on the complexity of the system, availability of system data, etc. One way of tackling the problem is by adopting a system of nested computer models, drawing information from the same source and supplying data to subsequent optimization stages. The performance of the generating units, fuel costs, system load and reliability criteria need to be properly simulated to obtain coherent results at all levels.

The operation planning itself may be subdivided into different horizons:

- **Long term**, normally one year subdivided in months. Long term operation planning is often used to establish the operation of seasonal reservoirs and fuel budgeting. The type and nature of optimization model adopted depends on the characteristics of the system being modeled.

- **Medium term**, up to one month subdivided in days. Provides the information about seasonal and weekly reservoirs as well as the operation of thermal power plants.

- **Short term**, up to one day subdivided in hours, half hours or quarter hours. It basically implies the optimum unit commitment and economic dispatch, with a suitable coordination of spinning reserve and under-frequency scheme.

An alternative to a nested system is to adopt models, which **combine long and medium term**, having a planning horizon of one or more years discretized in days.

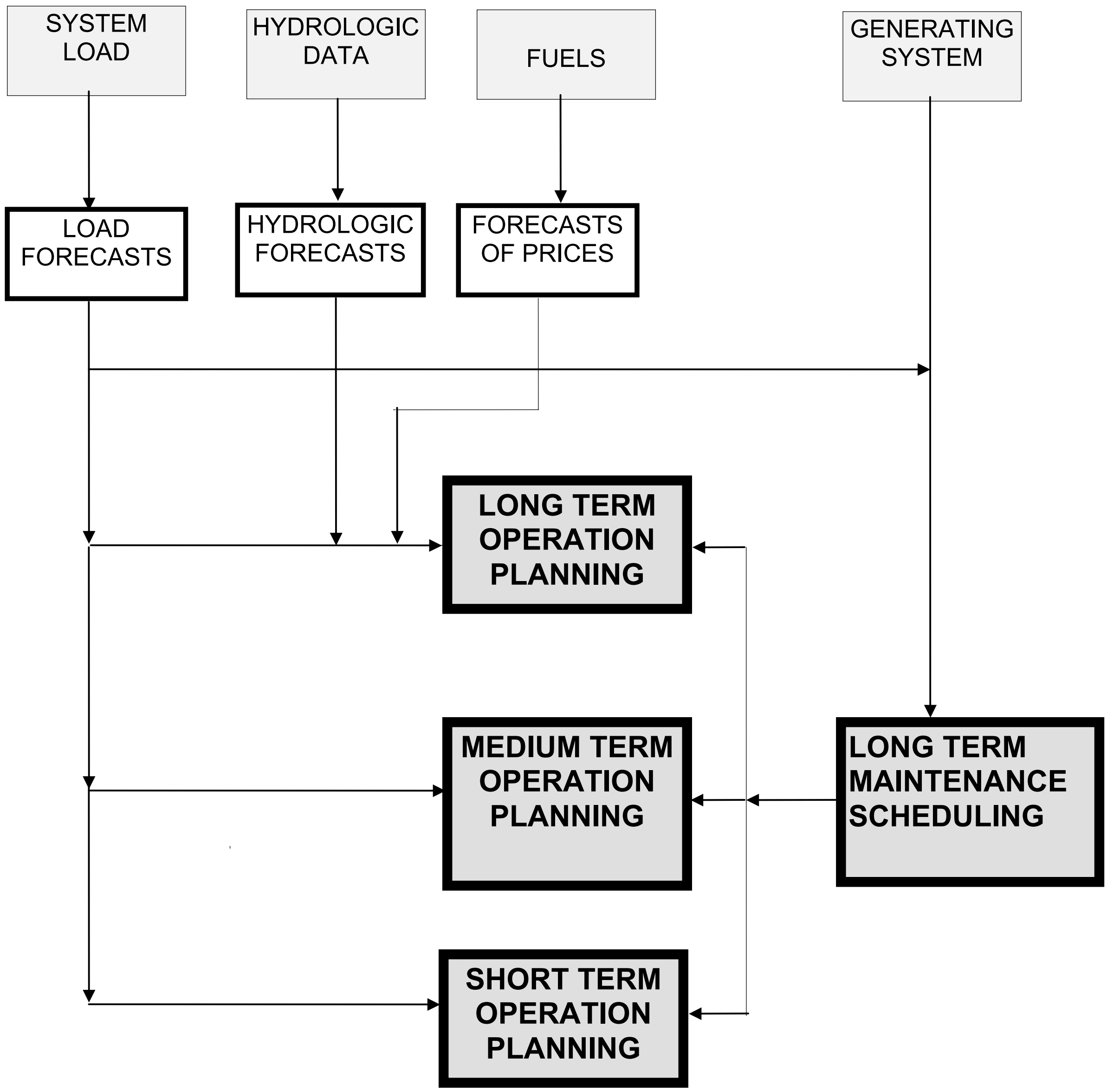


Fig. 5.6: Basic Activities In Operation Planning

Independent of the type of model adopted, information about the availability of the generating units is required at every level. Evidently, the availability of generating units, which is established through maintenance programs, has a direct impact on the system performance in terms of reliability and cost.

As a matter of fact, the optimization of operation and maintenance addresses a series of interrelated activities of different nature for which there is no closed-form solution. Therefore, the approach is to separate the overall problem into sub problems, which are optimized independently at a lower level and coordinated at a higher level to ensure a global optimum.

Although both operation planning and maintenance scheduling have the same planning horizon, these are treated in a separate way due to structural differences in the problem formulation. Operation planning deals with the optimization of mostly continuous variables, while maintenance scheduling is concerned with binary variables - either the units are available for operation or they are undergoing maintenance.

For this reason, the practice is to define first the maintenance schedule of the generating units before proceeding with the optimization of operation planning. Most likely, the opposite sequence would not work because the optimum solution for the operation planning will not necessarily satisfy the maintenance requirements or would restrict them to unfeasible levels.

There are important methodological aspects to be considered with regard to long and short term operation planning. While some parts of the long term operation planning may be considered as stochastic events, the short term operation planning is treated as a purely deterministic process satisfying reliability n-1 criteria.

The above mentioned activities comprise the complete generation system. Additionally to these, the maintenance works for each generating unit comprise a set of works of different nature to ensure that the required spare parts, material and manpower are available in time.

The main aspect to be considered in maintenance scheduling is the impact of the planned outages of the generating units on production costs, cost of imported energy from other power utilities and the system reliability. In this context, it is important to consider the adopted methods for maintenance scheduling and the maintenance cycles of different units.

5.4.2.2 MAINTENANCE OF GENERATING UNITS

Preventive and corrective maintenance comprise all activities aimed at keeping and recovering the nominal capacity as well as assessment of the prevailing conditions of the components of a system.

Preventive maintenance is normally carried out according to a program. It implies a procedure of periodically reconditioning a system in accordance with specific instructions and scheduling to prevent or reduce the probability of failure or deterioration while the system is in service.

Corrective maintenance of a system is generally undertaken to restore it to working order following failure, wear or deviation. It may include repair, replacement, etc.

The basis to undertake maintenance of a unit, block or plant is the maintenance strategy established for it. This defines the type, scope and frequency of the maintenance of the different components. It also defines the techniques, manpower, materials and time required to execute the maintenance activities. Needless to say, a well established maintenance strategy is, for the interconnected system, economically very important, having impact on direct and indirect costs.

The generation costs of each system component depend on the capacity and production. For planning purposes, these are used to determine marginal costs, which in turn constitute the basis to define the tariffs, for sizing of new projects, etc.

Capacity costs comprise the investment costs of the unit including auxiliaries, civil works, administration, taxes, insurances, personnel, etc.

Production costs result from the consumption of fuels, lubricants and other materials, maintenance and taxes.

The maintenance costs are incurred by the own personnel, contractors, materials, tools and stock management. The maintenance costs are affected by the mode of operation and therefore depend on the production. Since the maintenance costs cannot be so easily assessed as the fuels costs, these are often estimated on basis of the type of plants and installed capacity. This is especially done for capacity expansion studies.

The requirements for preventive maintenance, such as costs of personnel and materials, directly depend on the maintenance strategy. Normally the personnel in charge of the maintenance can estimate these costs. The result is a maintenance cycle with indication of the frequency, time difference between sequential maintenance, duration of each maintenance, etc. The unavailability of generating units is defined by the frequency and duration of the maintenance.

On the other hand, the maintenance strategy affects the reliability of the system. Both scheduled and unscheduled outages of the units affect the costs in interconnected system, especially when expensive units have to be operated to cover the absence of the cheaper ones.

The impact of the maintenance strategy on the reliability of the generating units has been very seldom quantified. The main reason is the large volume of data required. It is empirically known that the reliability decreases with an increase in the time between maintenances.

The maintenance costs are also indirectly affected by the maintenance strategy through the outages of the generating units, which induce costs for recovery of failures and repairs. This relationship is usually not exactly known and could only be established through an analysis of the statistics of failures for units of similar characteristics, under similar loading conditions, with similar maintenance strategies, etc. This has not been done up to now and is therefore roughly estimated.

Besides the maintenance costs, additional costs are incurred due to monitoring. These are almost independent of the maintenance strategy. These activities comprise monitoring and checks as well as the maintenance of stand-by, backup and redundant elements.

Due to the many different effects of the maintenance strategy on the interconnected system, the definition of an optimal maintenance strategy for each unit is a very complex problem by itself. However, a quantitative definition of all interdependencies is not possible, which unfeasible the formulation of the problem in mathematical terms. Therefore, the maintenance strategy is the result of experiences, requirements, specifications, etc. of persons and institutions involved.

There are certain requirements from organizations, insurance companies, etc. which require inspections within certain intervals. Very often follow the maintenance schedules these deadlines. Additionally, the know-how of the manufacturers and the experience of the personnel in charge. Significant improvements have been achieved through the evaluation of statistical data about faults, damages, costs and availability.

Very important in any case is the possibility of quantifying the cost of a modified availability.

5.4.2.3 SCOPE

The definition of a maintenance strategy for a unit and the maintenance planning for the whole system are very important to achieve an efficient and economic electricity generation. The purpose of HTMS is to assist in the development of optimal maintenance programs for interconnected electric systems in accordance to maintenance cycles, keeping in view generation costs and reliability.

A direct result of the maintenance strategy for a given unit is its maintenance cycle, which implies the frequency and duration of maintenance activities. The maintenance strategy has an impact on the maintenance costs and on the repair costs through unscheduled outages and the reliability.

The maintenance program affects the cost of generation and the reliability of the system. Therefore, the maintenance of a cheap unit requires its replacement through a more expensive one. Additionally, the scheduled outage leads to reduction in the system reliability. The selection of reliability levels of supply may affect through the outages foreseen in the maintenance programs at the time of addition of new capacity, required to ensure the desired reliability levels. Similarly affected are the capacity and energy costs as well as the system reliability.

HTMS is a tool, which determines how the production costs may change due to different maintenance strategies and programs. It minimizes the total operation costs over a given time period taking into consideration the system reliability.

5.4.3 MAINTENANCE SCHEDULING

5.4.3.1 GENERAL

Due to the complexity of the procedure, HTMS will be useful in case of power systems where system reliability is a relevant planning and operational parameter and maintenance scheduling is carried out on regular basis.

Relevant aspects to be considered in maintenance scheduling are:

Power Mix

The availability of different types of power stations, fuels and mode of operation may lead to a significant variability in the production costs as well as reliability levels.

Load Fluctuations

The variability of the load defines the periods when sufficient scope is available to program the maintenance of the units. The number of possibilities and the magnitude of the optimization problem increase with the available space. On the other hand, it becomes a difficult task to find a feasible maintenance schedule when the system is heavily loaded.

The load factor may be used as an index to assess the loading of the system. A relatively low yearly load factor may be an indication of seasons (winter or summer) in which idle capacity is available. A high value means that the load has a uniform distribution throughout the year.

When planning the maintenance of the units, the availability of personnel should also be considered. It may be that the periods with lower loads coincide with vacations.

5.4.3.2 MAINTENANCE CYCLES

The maintenance cycles of a generating unit indicate the frequency and duration of maintenance works. These vary according to type and maintenance strategy. In any case, the aging and technology play an important role in the frequency of maintenance works. Modern equipment allows longer periods between maintenance due to better designs and more advanced monitoring equipment.

Following considerations provide some general guidelines:

Boiler

Comprises inspection of the boiler, cleaning and replacement of worn out and damaged parts of the boiler and auxiliary equipment. The internal inspection may take place at least every 3 years and the water pressure test at least every 9 years.

Steam Turbine
If required, it defines the maintenance of the unit. Otherwise, the maintenance of the boiler is decisive. The size of the units has less influence because larger units also require more personnel.

Gas Turbine
Normally require frequent and long maintenance periods due to the wear induced by frequent starts.

Nuclear
The maintenance is carried out in connection with the replacement of burning elements. These take place normally once a year.

Hydropower
The maintenance takes place every year in the periods when flows are low and some capacity remains idle. The frequency and duration varies with type and age of the turbines. However, normal maintenance works may take place on yearly basis while main works are required after some years.

5.4.3.3 GENERAL CHARACTERISTICS OF MAINTENANCE WORKS
Maintenance scheduling is a part of the long term operation planning. Long-term maintenance programs over various years may be developed. However, due to the maintenance cycles, seasonal fluctuations of the load and the hydrologic cycle, there is a natural trend to program the maintenance on a yearly basis.

Longer periods are normally not adopted mainly due to uncertainties in:

- Power demand, which in many cases is strongly weather dependent
- Available discharges for power generation
- Fuel prices
- Unexpected additional maintenance works not foreseen at the planning stage
- Availability of personnel, parts, etc.

The maintenance begins in many countries during Friday, after the peak load to allow the cooling of the thermal units. It finishes the next Friday, just after normal working hours. Therefore, for a given week the units is either ready for operation or undergoing maintenance.

Therefore, the practice is to subdivide the planning horizon into 52 time steps of one week duration each, beginning and ending on Friday evening.

5.4.4 BRIEF DESCRIPTION OF HTMS
There are different approaches for maintenance scheduling. These basically comprise:
- Manual methods
- Heuristic methods:
    - Levelized reserve (i.e. Reserve Capacity and Reserve Rate methods)
    - Levelized risk
- Methods based on mathematical programming:
    - Linear Programming
    - Network Flow
    - Mixed Integer Linear Programming
    - Dynamic Programming

HTMS is a software package, which optimizes the maintenance scheduling of hydrothermal systems. Two different approaches are possible:

- Heuristic based on Levelized Reserve Method
- Mixed Integer Linear Programming (MILP)

In either case, the results of the optimization are the deadlines for the beginning of the maintenance of each plant/block. The planning horizon is discretized as follows:

- Duration of planning horizon: one or more years
- Time step: one week (7 days/week)

This discretization is highly suitable for start-up and shutdown cycles of thermal power plants. After undergoing maintenance, these can be operated with full capacity at the end of the maintenance period.

As in case of every software package, the results will be as good as the input data. Therefore, a thorough understanding of the system is required to achieve useful results.

The program comprises following modules:

- REVISION
- HTSLDS
- PRE_MILP
- LP_SOLVE
- RESULTS

The relationship among the modules is schematically shown in Fig. 5.7. A brief description is given in the following paragraphs.

5.4.4.1 REVISION
At this level, 2 options exist for the selection of the method to be used.

- Heuristic
- Mixed Integer Linear Programming

The selection made at this stage will affect the sequence of calculations and the results obtained.

The module includes very efficient algorithms which basically carry analysis of the general maintenance program and establishes for every week all feasible maintenance combinations for all the blocks/plants, taking into account:

- Window during which the maintenance is allowed.
- Not allowed simultaneous maintenance of blocks/units.
- Allowed maximum capacity under maintenance.
- Minimum reserve requirements.

The purpose of this module is to reduce the search corridor in order to allow a faster determination of the optimum solution.

WINDOW
The maintenance strategy defines the period, or window, during which the maintenance of each unit can take place. Since the size of the optimization problem increases according to the number of combinations, the windows should be realistically set to avoid unnecessarily long processing times.

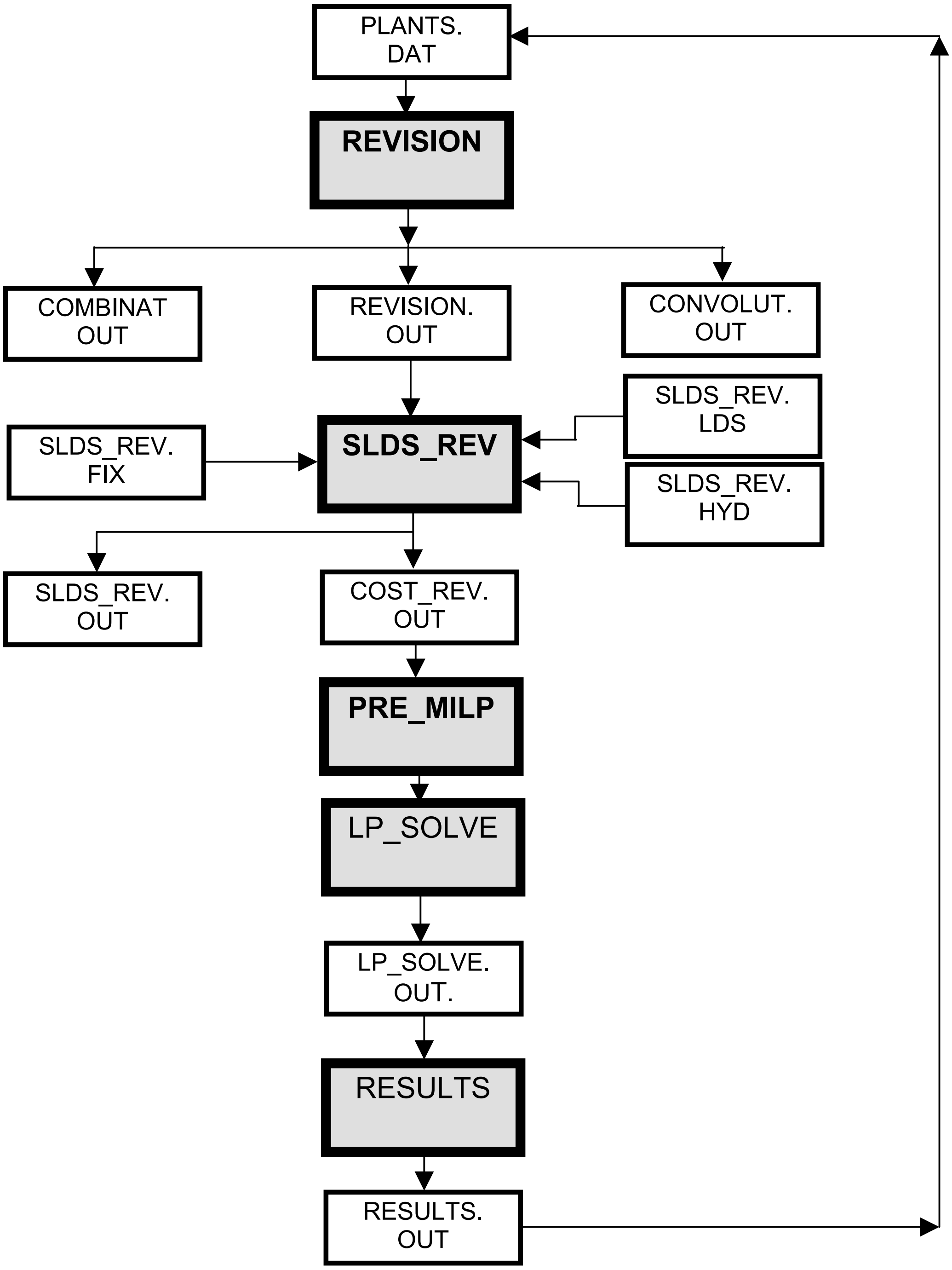


Fig. 5.7: Flow Chart of HTMS Modules

Since there are only two possibilities for every unit - either ready for operation or in maintenance - the maximum number of combinations is 2^{np}, where np is total number of units, which can undergo maintenance during the week under consideration.

SIMULTANEOUS MAINTENANCE

The definition of the windows for all units automatically covers the case of the plants, which can be maintained simultaneously.

On the other hand, in case of overlapping windows, it is necessary to specify those units, which cannot be taken out of service at the same time.

ALLOWED MAXIMUM CAPACITY UNDER MAINTENANCE
There may be technical constraints, which limit the maximum capacity, which can be under operation at the same time during certain period of time. This may be due to contracts with large consumers, suppliers, storage limitations, etc.

This constraint may not be always tight, as the reserve requirements may already limit the maximum capacity undergoing maintenance.

RESERVE REQUIREMENTS
The required minimum reserve is a parameter, which is set by each power utility according to quality standards, contractual obligations, etc. The reserve is affected by:
- Outage of the units
- Primary governing
- Weather
- Load fluctuations

The reserve requirements are calculated on basis of an outage duration curve determined on basis of the outage rates of the different units in operation. A recursive algorithm, basically a convolution, is used to calculate the cumulative outage rate.

The loss of capacity is determined on basis of the specified loss of load probability (LOLP) level through interpolation on the curve of cumulative outages.

INPUT DATA
The basic data requirements comprise:

General:
- Number of units/blocks/plants
- Length of planning horizon, in weeks

For each units:
-Plant name
-Plant capacity, in MW
-Outage rate
-Maintenance number
-Allowable window, in calendar weeks
-Duration of the maintenance, in weeks
-Min/Max time span in weeks with respect to previous maintenance

Simultaneous Maintenance:
Number of plants for which simultaneous maintenance are allowed. Normally this is already covered in the definition of the window

Simultaneous Maintenance:
Number of plants for which simultaneous maintenance are NOT allowed.
Maximum Capacity in Maintenance:
In MW

Reserve requirements
-Maximum acceptable loss of load probability level
-Available system reserve, in MW
-Minimum system reserve required, in MW

5.4.4.2 HTSLDS

Carries out a stochastic load dispatch simulation for hydrothermal systems for all feasible combinations of each week of the maintenance-scheduling period.

The program determines the total production costs for every week and each feasible combination. Besides the costs incurred by the fuel consumption of the thermal plants, the program also determines the LOLP and the associated cost of unserved energy.

STATE MODEL

The general state model of a plant is shown in Fig. 5.8. It covers all possible maintenance stages of all types of generating plants, including nuclear power plants. The stages are:

- Normal operation, with capacity P_N

- Stretch out period, with $P < P_N$. Stretch-out is a procedure normally adopted in case of nuclear power plants. The purpose is to achieve a maximum exploitation of the fuel elements before their replacement.

- Shut down, which can be either partial or total. The required time to allow cooling of elements of thermal power plants is included as part of the maintenance.

- Maintenance period, which may last one or more time steps

- Start up, after maintenance has been completed. The capacity may be enhanced through improvements. The required time to allow warming up of elements of thermal power plants is included as part of the maintenance.

The procedure before maintenance for conventional thermal and hydroelectric plants is covered through a stretch out period of zero length.

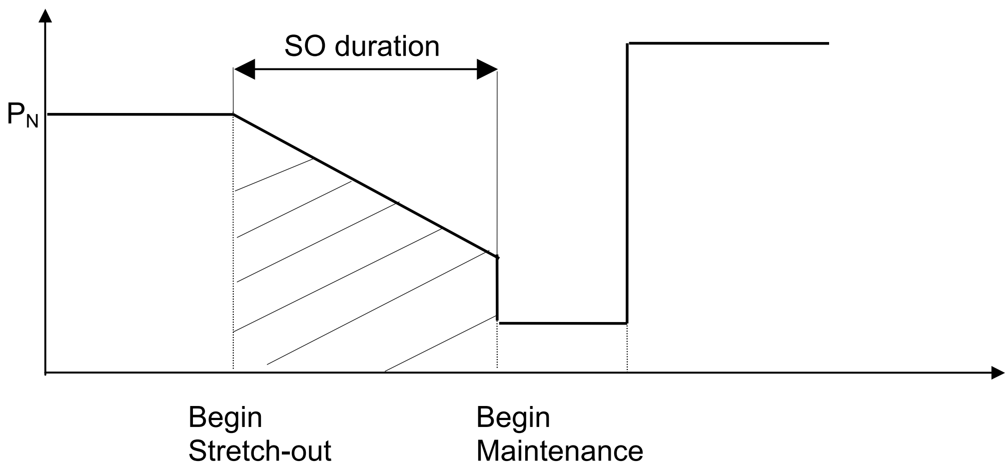


Fig. 5.8: General State Model

INPUT

The data required to run this module comprises:

- Feasible combinations
- Fixed system data
- Variable system data

FIXED DATA

The fixed system data is stored in the file slds_rev.fix. It comprises data such as:

- General system characteristics
- Fuel type and cost
- Cost of unserved energy
- Hydropower plants: number of units, capacity/unit, etc.
- Thermal plants: number of units, capacity/unit, fuel type, specific fuel consumption, FOR, etc.

VARIABLE DATA

The variable data is classified in two categories:

- System load
- Output of hydroelectric plants
- Availability of generating plants

SYSTEM LOAD

File slds_rev.lds contains the weekly load data, basically:
- Peak weekly load
- Minimum weekly load
- Weekly energy

HYDROELECTRIC OUTPUT

File slds_rev.hyd contains the weekly data relevant to the output of the hydroelectric plants. This data has to be determined externally with suitable procedures and comprises a factor which indicates for each plant the availability of peaking capacity as well as the total weekly energy available.

SYSTEM AVAILABILITY

The availability of the units is determined from the results produced by module COMBINA. State models are generating accordingly for each combination and week.

OUTPUT

The most important input for the next module (pre_milp) is the total production cost for each week and combination. However, detailed information about the stochastic load dispatch simulation is also stored on a computer file. For every week and combination the program produces the following 6 tables summarizing the results of the simulation:

- Available power resources
- Dispatched power
- Available energy resources
- Dispatched energy
- Fuel consumption
- Fuel cost

Additionally, the corresponding costs for each week and combination are stored on a computer file, which is used for the formulation of the optimization problem.

5.4.4.3 PRE_MILP

Prepares input files for mixed integer linear programming (MILP) for the whole scheduling period on basis of the allowed weekly combinations and their corresponding generation costs. The organization of the optimization problems is as follows:

OBJECTIVE FUNCTION

Keeping in view that only one combination z(t,i) is possible every week , the objective function considers the minimization of the cost of all combinations for the total planning horizon nw.

$$\sum_{t=1}^{nw} \sum_{i=1}^{nc(t)} z(t,i) \bullet Cost(t,i) \rightarrow \min$$

RESTRICTIONS

1. Only one combination z(i,j)allowed every year

$$\sum_{i=1}^{nc(t)} z(t,i) = 1 \qquad \text{for all } t = 1, 2, \ldots nw$$

2. The units y(i,j) should be maintained at least once over the planning period

$$\sum_{t=1}^{nc(t)} y(t,j) = 1 \qquad \text{for all } t = 1, 2, \ldots nw \quad j=1,\ldots,np$$

3. The link of z and y variables is ensured through:

$$\sum_{t=t-dur(j)+1}^{t} y(t,j) = \sum_{i=1}^{nc(t)} y(t,j) \bullet f(t,j,i) \qquad \text{for all } t = 1, 2, \ldots nw \quad j=1,\ldots,np$$

f(t,j,i) = 1, when unit j is in combination i and under revision in week t
= 0, otherwise

4. z(t,i) and y(t,j) are integer and nonnegative.
5. Other constraints can also be added to satisfy other requirements.

STRETCH OUT MODELS FOR NUCLEAR POWER PLANTS

In case of nuclear power plants, the aim is always to achieve a maximum utilization of the fuel in stretch-out (SO) operation. Therefore, any reduction in the length of stretch out period will lead to a partial use of the remaining fuel in the next cycle. This aspect is accounted for through a penalty which should be included in the objective function through a set of additional decision variables.

Stretch-Out Model 1

- Fixed begin of maintenance
- Variable begin of stretch-out
- Penalty for delaying begin of stretch-out

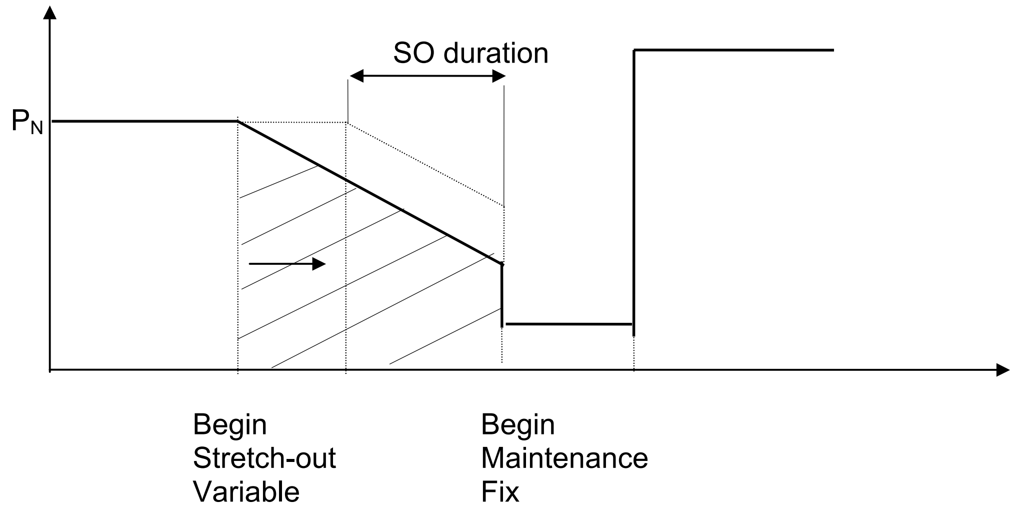


Fig. 5.9: Stretch Out Model 1 for Nuclear Power Plants

Stretch-Out Model 2

- Variable begin of maintenance
- Fixed begin of stretch-out
- Penalty for earlier begin of maintenance

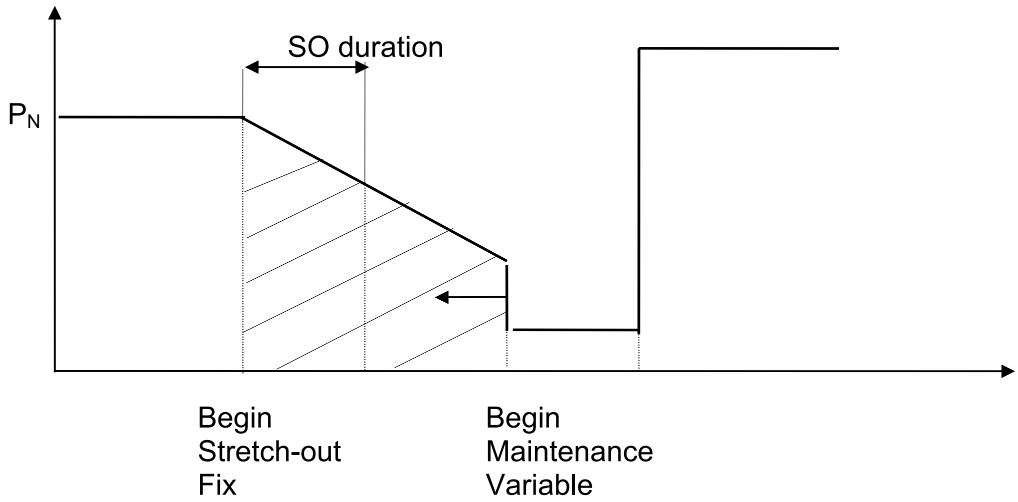


Fig. 5.10: Stretch Out Model 2 for Nuclear Power Plants

Stretch-Out Model 3

- Variable begin of maintenance
- Variable begin of stretch-out
- Fixed duration of stretch-out
- No penalty is considered

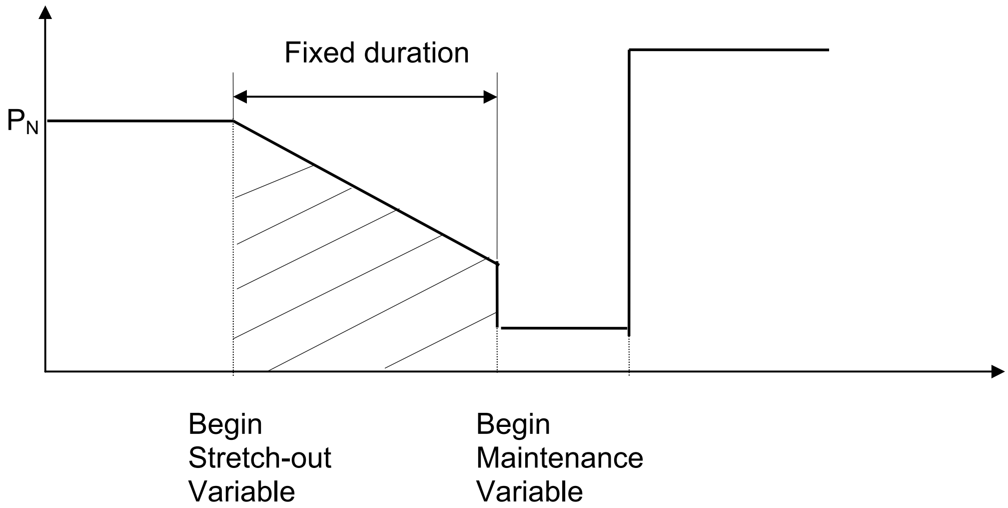


Fig. 5.11: Stretch Out Model 3 for Nuclear Power Plants

The consideration of stretch-out operation requires the inclusion of a new set of integer variables, which account for the lost energy (E_{loss}).

The objective function takes the form:

$$\sum_{t=1}^{nw} \sum_{i=1}^{nc(t)} z(t,i) \bullet Cost(t,i) + E_{loss} * PF \rightarrow \min$$

PF is the penalty factor and E_{loss} corresponds to the difference between the energy generated according to a normal stretch out program (ESO_{max}) and the energy produced either by following models 1 or 2 (ESO):

$$E_{loss} = ESO_{max} - ESO$$

The problem can be solved through a stepwise representation of the stretch out process, as schematically presented in Fig. 4-6.

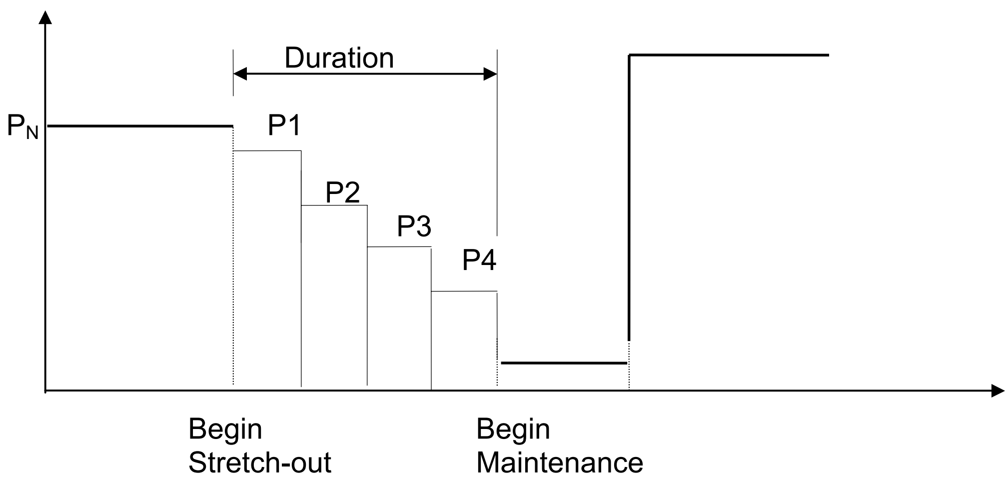


Fig. 5.12: Discretized Stretch Out Model

Since ESO_{max} is a constant, the objective function takes the form:

$$\sum_{t=1}^{nw} \sum_{i=1}^{nc(t)} z(t,i) \bullet Cost(t,i) - \sum_{j=1}^{nn} \sum_{k=1}^{nso} P(k)*x(k,j)*PF \rightarrow \min$$

The variables x(i) are integer, requiring to fulfill the constraints:

$x(1,j) \geq x(2,j) \geq .... \geq x(n,j)$

$y(j) \geq x(1,j)$

OUTPUT
The program prepares an input file with specific format from program lp_solve. However, an output file can also be produced in MPS format for other optimization packages..

5.4.4.4 LP_SOLVE
Depending on the size and number of units of a system, the number variables and constraints can be very large. Therefore, there is a need to apply efficient algorithms, which can also ensure an optimum solution. lp_solve is a general algorithm for the solution of mixed integer linear programming (MILP) problems which uses a simplex algorithm and sparse matrix methods for pure LP problems. It uses an iterative on branch and bound algorithm when integer variables are included. The program can handle up to 30,000 variables and 50,000 constraints.

Various options are available to control the execution of the optimization process, such as:

- Printing of intermediate results of branch-and-bound
- Printing of dual variables
- Specification of bounds
- Accuracy to check whether variable is integer
- Printing of intermediate valid solutions

5.4.4.5 RESULTS
The program carries out an analysis of the output produced by lp_solve and presents the results of the MILP optimization in easily understandable form. The results are basically:

- For every unit/block: week when maintenance begins
- For every week: units/blocks under maintenance

Different options are also available to obtain more detailed information.

5.5 MEDIUM AND LONG-TERM OPERATION PLANNING
It normally has a horizon of one year, subdivided in moths, 10-daily or weekly time steps. Comprise different algorithms to optimize the operation of hydrothermal systems keeping in view the requirements of the consumers, availability of resources and system constraints. The results are:

- Reservoir releases
- Power and energy output of each plant in the system
- Fuel requirements and costs

5.5.1 RESERVOIR OPERATION

Tools based on mathematical programming techniques have been developed in recent years for the optimum use of water resources systems. The availability of personal computers further contributed to in the application of these tools to real world problems.

5.5.1.1 OBJECTIVES

There are a large number of computer programs developed to optimise the operation of complex multiple purpose reservoir systems. Many models have been developed for this purpose, both deterministic and stochastic. However, most of the models fulfil research requirements and only a few have been applied to real world problems. Frequently, the models apply to single system and changes in the characteristics of the system require modifications in the computer code.

HYDOP is a deterministic model, which optimises the water use in complex multiple purpose reservoir systems. The idea behind HYDOP is to have an efficient computer model, which can be applied to a wide variety of systems. The topology of the system and the characteristics of the system components are defined externally.

5.5.1.2 METHODOLOGY

The model is based on the application of Linear and Dynamic Programming techniques to optimise the system operation. Keeping in view the characteristics of multiple purpose reservoir systems, highly efficient algorithms can be applied to satisfy requirements concerning computer capacity and computational time.

The optimisation for every time step is achieved through a primal network algorithm, which considers all water demand and characteristics of conduits and reservoirs in the system. Upper and lower limits are implicit parameters in the computations. An efficient iterative procedure is used to account for non-linearities. Convergence is ensured and achieved after a few iterations.

Normally, optimum operation rules are obtained with the application of the primal network algorithm. However, when trade-offs among different water uses exists, Dynamic Programming is applied to establish the optimum solution over the total planning horizon. The objective function of such algorithm is the maximization of the potential energy stored in the system.

5.5.1.3 INPUT DATA

The data requirements of HYDOP comprise both fixed parameters which define the physical characteristics of the system (fixed data) and information which varies with time (variable data).

FIXED DATA

The fixed information comprises a topological description of the system in terms of:
- Number of water conduits and river reaches
- Number of nodes conforming the system
- Number of reservoirs
- Number of power stations

Besides, to manage the water resources in the system following data is needed:
- Number of inflow time series
- Number of water demand time series
- Number of gains and losses time series
- Number of simulation periods

The topological arrangement is indicated through a network formed by links and nodes. Links are basically water conduits (canals, tunnels, etc) while the nodes correspond to the location of reservoirs and other junctions in the system. All links need an indication of upper and lower bounds, which correspond to maximum capacity and minimum requirements respectively.

Power stations are referred to water conduits while system inflows, water demands, gains and losses are referred to nodes in the network.
Reservoir data comprises elevation-area-volume relationships. The data is given in tabular form and the program interpolates the values linearly. Therefore, a suitable discretization is always desirable.

The characteristics of power stations are defined in terms of production functions, which are given in the form of net head available, specific water consumption and power output. Normally these functions are derived on basis of measurements in the different power stations. These functions implicitly account for head losses in the water conduits, cavitation limits, efficiency of the turbo-generator units, etc.

VARIABLE DATA
The variable data is given for every time step of the planning horizon. The information refers to water availability and requirements.

Inflows are required as deterministic time series, which may have been defined on basis of hydrologic forecasts, water accords, contracts, etc. Similarly, water demands, which may be for irrigation, water supply and other water uses are also given as deterministic values.

Gains in the systems often occur in some river reaches where ungauged inflows may occur. Losses on the other hand may occur due to direct evaporation from the water surface in wide river reaches, evapotranspiration of plants, seepage, etc. The information is required to avoid mismatches in the water balances in the system. These problems normally occur in very large river systems, where intensive water uses and large seasonal variations do not allow to properly quantify these phenomena.

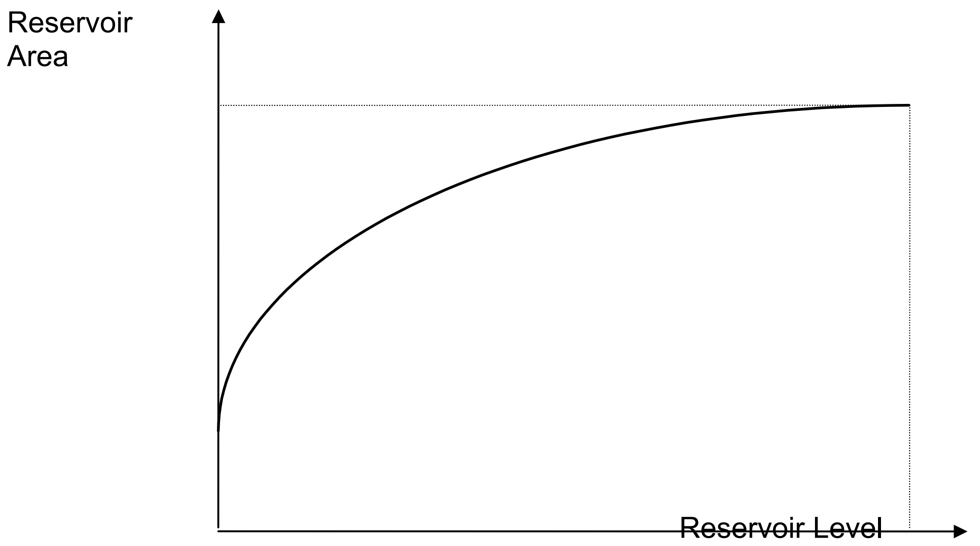
OUTPUT
HYDOP allows different levels of output according to the needs. The basic output provides information about:

- Expected production of the power stations in the system
- Operation of the reservoirs
- Deficits due to unsatisfied water demands

More detailed information can be obtained, especially with regard to the flow in every water conduit of the system. The output is presented in tabular form for every time period of the whole planning horizon. Depending on the size and complexity of the system, the detailed output can be very large.

5.5.1.4 DIMENSIONS AND LIMITS
In its present PC version HYDOP allows:
- 50 links
- 50 nodes
- 10 reservoirs defined with up to 50 sets of elevation-area-volume values
- 10 power stations defined with up to 50 sets of head-discharge-output values
- 10 inflow series
- 50 demand series
- 50 gains/losses series

However, these limits can be easily extended according to the requirements.



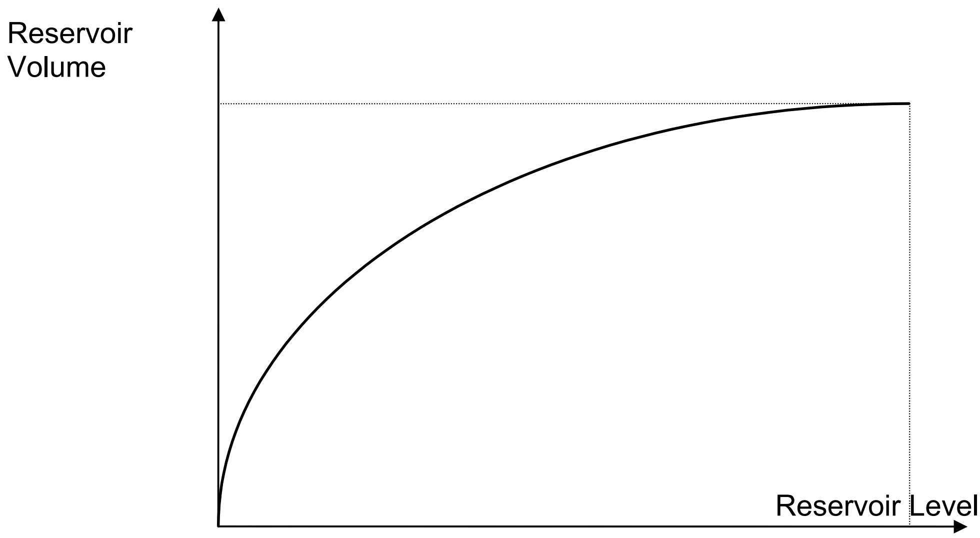
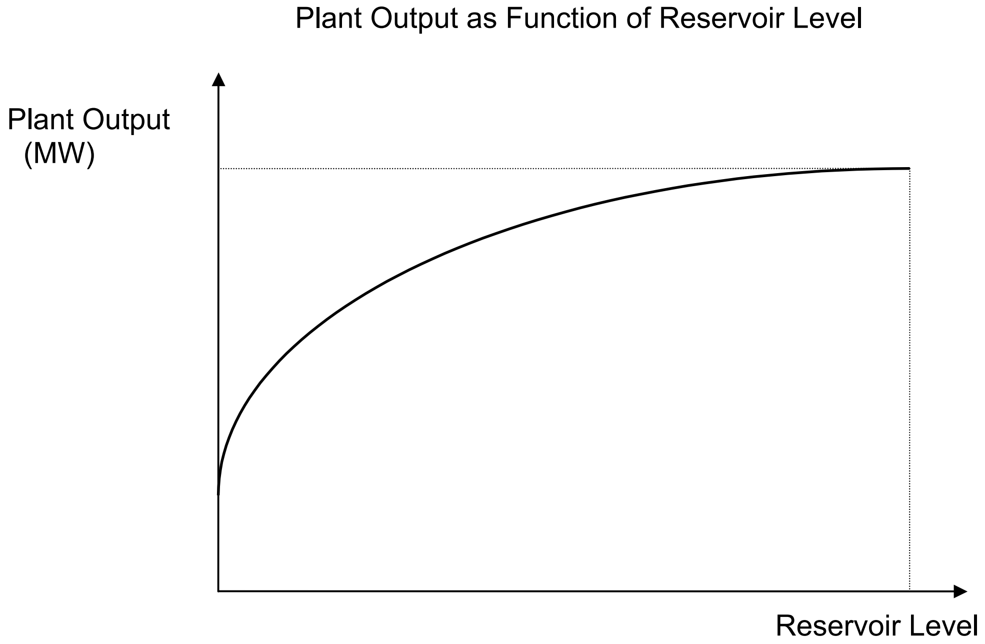


Fig. 5.13: Reservoir area-elevation-capacity curves



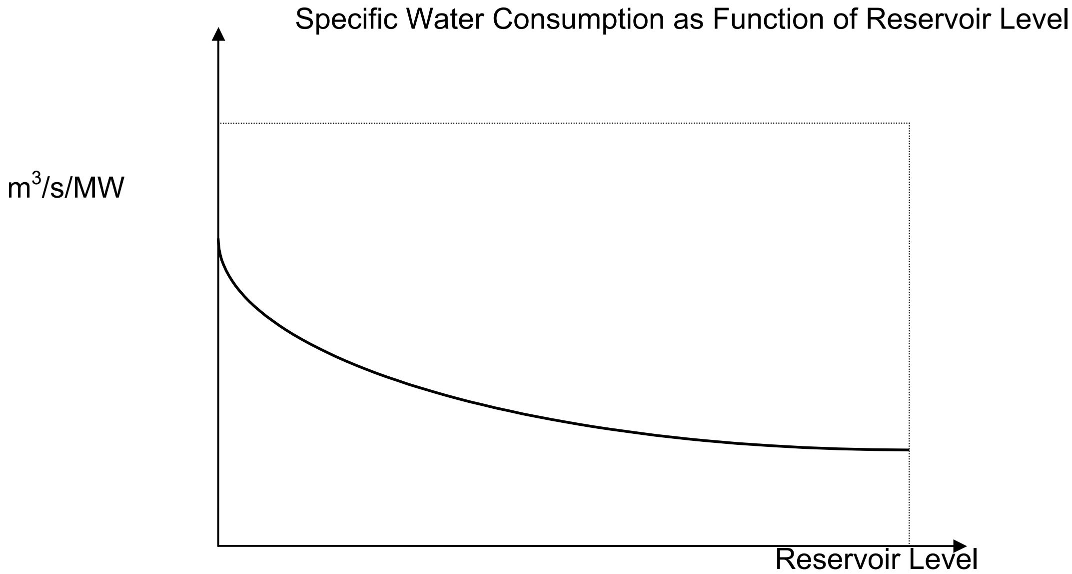


Fig. 5.14: Typical production functions for hydroelectric plants

5.5.2 DETERMINISTIC HYDROTHERMAL DISPATCH/INTEGRATED LOAD DURATION CURVE

There are different algorithms available for the long-term simulation of operation of hydrothermal systems. In this regard, two main categories can be established:

- Deterministic models
- Stochastic models

In the following paragraphs a description of a deterministic model is given.

5.5.2.1 METHODOLOGY

The program allows the deterministic simulation of monthly dispatch (production) of hydrothermal system on basis of the Integrated Load Duration Curve, having as objective function the minimization of generation costs incurred through the operation of thermal power plants. The purpose of the program is to serve as a simple to use tool to simulate different scenarios in a short time.

The use of the Integrated Load Duration Curve allows the implementation of efficient algorithms to determine the best location of the generating units. This is done through fitting analytical functions to the various parts of the curve, as shown in Fig. 5.15 and described in detail in Appendix 3.

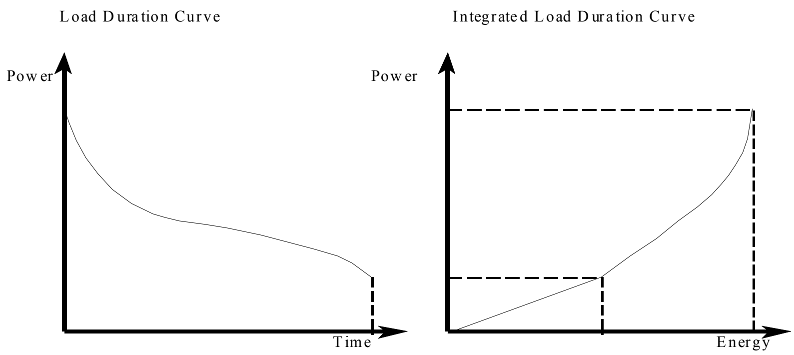


Fig. 5.15: Integrated load duration curve

The commitment of the generating plants is made following a merit order determined on basis of average generation costs, as follows:

a) Use of hydroelectric energy is maximized
b) Thermal generation is decided according to a merit order table determined on basis of average generation costs in order to cover the demand not satisfied by hydro generation.

Hydroelectric generation is dispatched in the form of an equivalent plant having the capacity and generation of the added output of the available plants for the time period under consideration. The adopted procedure is schematically shown in Fig. 5.15.

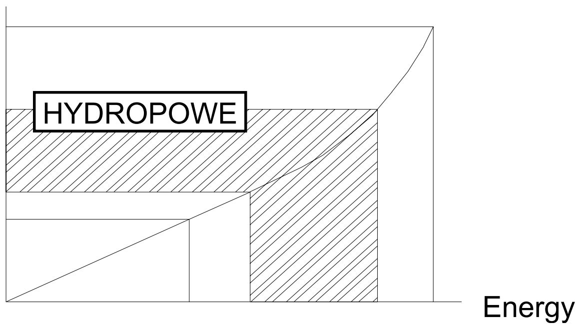


Fig. 5.16: Dispatching of Hydropower Plants

Generation is made strictly on basis of merit order, in accordance with the average generation costs. Therefore, the plants are sequentially selected from lowest to highest cost, until the demand is completely covered. The adopted procedure is schematically shown in Fig. 5.17.

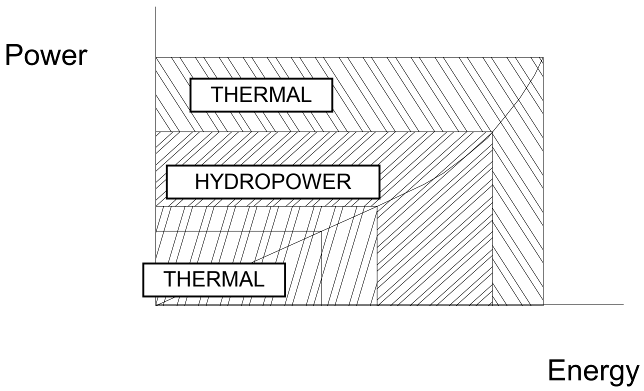


Fig. 5.17: Dispatching of Thermal plants

5.5.2.2 RESULTS

Six tables with monthly information of units dispatched are produced as follows:

- Power resources
- Power dispatch
- Energy resources
- Energy dispatch
- Fuel consumption of thermal units
- Generation costs of thermal units

5.5.3 STOCHASTIC HYDOTHEREMAL DISPATCHING

The following paragraphs contain a description of a stochastic model.

5.5.3.1 METHODOLOGY

The use of the Equivalent Load Duration Curve allows the implementation of efficient algorithms to determine the best location of the generating units. This is done through a discretization of the curve in terms of power and time, as shown in Fig. 5.18.

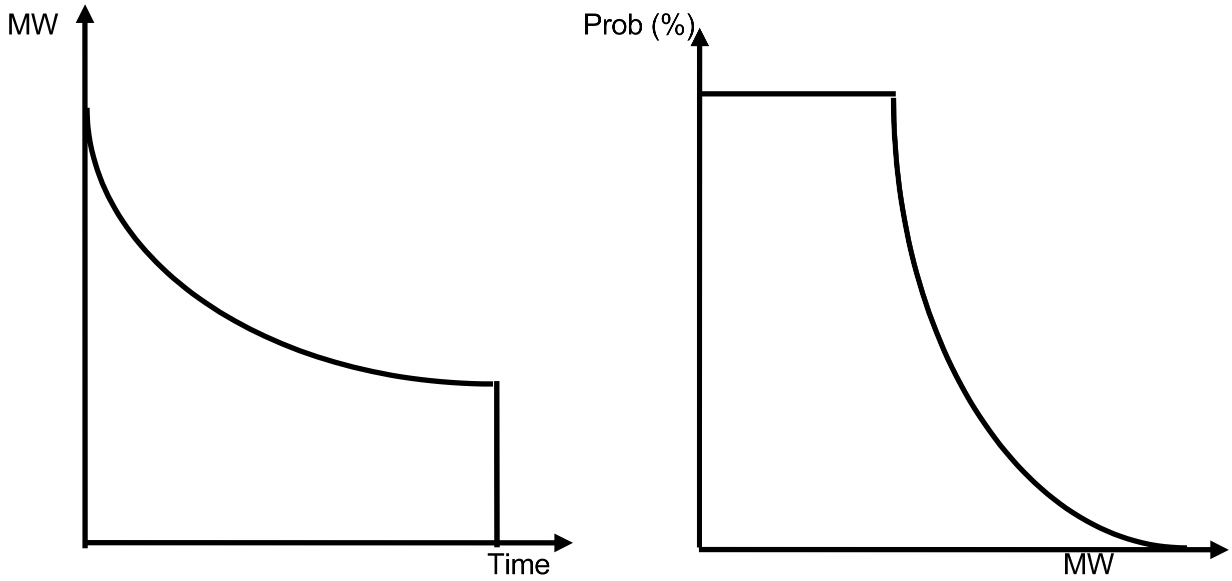


Fig. 5.18: Load Duration Curve vs. Equivalent Load Duration Curve

The dispatch of every plant, or block, of capacity C is made by convoluting the available power according to the equation:

$$P'(x) = qPn(x) + pPn(x + C)$$

where:

q = probability that C MW are unavailable
p = 1 - q = probability that C MW are available

P'(x) = probability of needing X MW after C MW have been dispatched
Pn(x) = probability of needing x or more MW
Pn(x + C) = probability of needing (x + C) or more MW

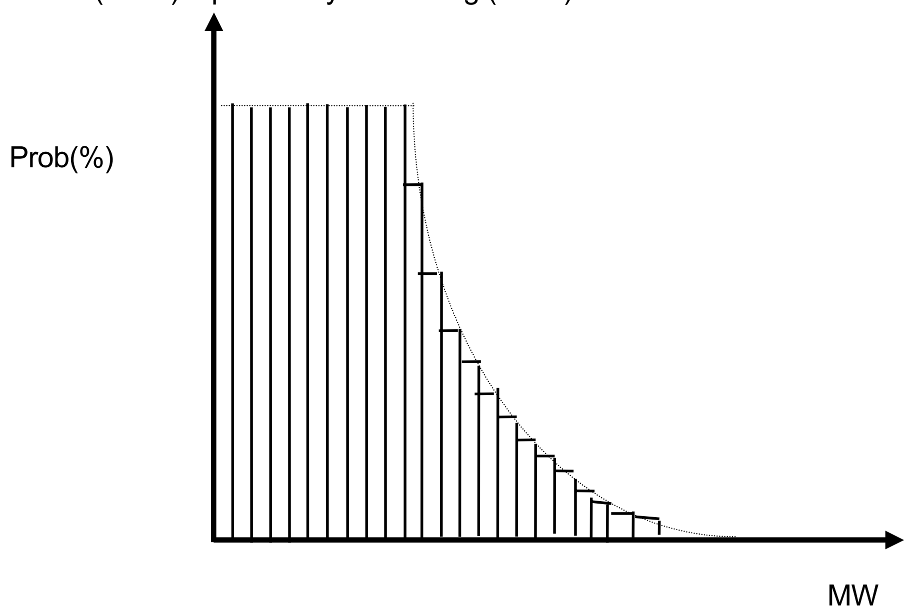


Fig. 5.19: Discrete Equivalent Load Duration Curve

This recursive algorithm constitutes the basis for convoluting the generating units. An inverse algorithm, called deconvolution, is also needed in case of dispatching the units in different blocks.

The commitment of the generating plants is made following a merit order determined on basis of average generation costs, as follows:

- Use of hydroelectric energy is maximized
- Thermal generation is used to cover the demand not satisfied by hydro generation

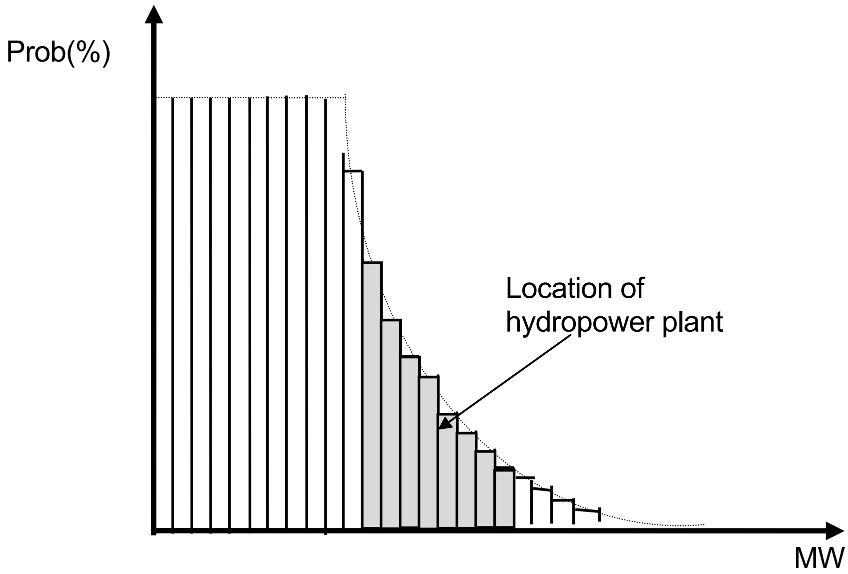


Fig. 5.20: Dispatched hydroelectric generation

- Each plant independently
- As an equivalent plant having the capacity and generation of the added output of the available plants for the time period under consideration.

The adopted procedure is schematically shown in Fig. 5.21. It is assumed that hydroelectric plants are restricted in terms of power and energy.

Thermal generation is made strictly on basis of merit order, in accordance with the average generation costs. The thermal plants are sequentially selected from lowest to highest cost, until the demand is completely covered or the last plant has been dispatched, whichever comes first. Units can be dispatched in various blocks, allowing in this manner the inclusion of "must-run" units. The adopted procedure is schematically shown in Fig. 5.21.

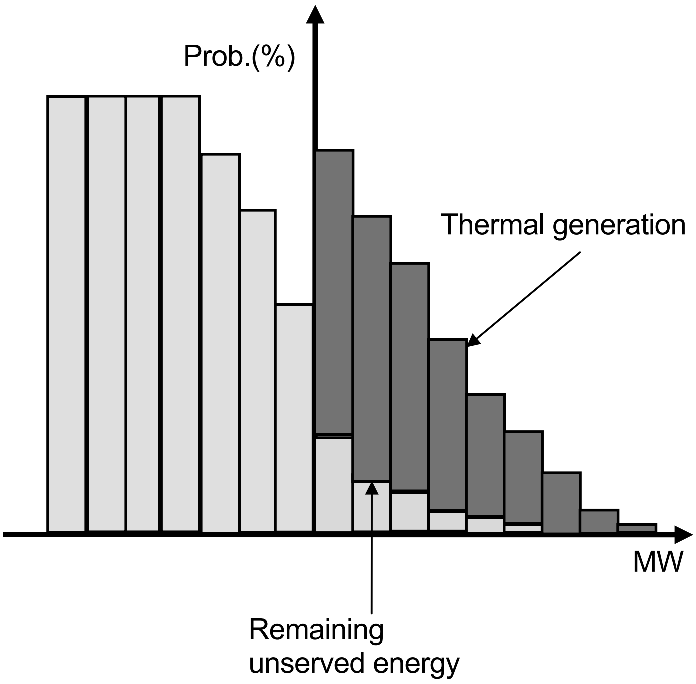


Fig. 5.21: Dispatched thermoelectric generation

5.5.4 RESULTS

Six tables with monthly information of units dispatched are produced as follows:

- Power resources
- Power dispatch
- Energy resources
- Energy dispatch
- Fuel consumption of thermal units
- Generation costs of thermal units

5.6 SHORT-TERM OPERATION PLANNING

With a horizon of one or more days, comprises the operation of hydro- and thermoelectric plants. Takes into consideration:

Generation:

- Unit commitment and economic dispatch
- Cost minimization
- Reliability requirements
- Coordination of spinning reserve and the load shedding (under-frequency) scheme
- Start-up and shut-down costs
- Hourly operation costs and marginal costs

The optimum economic dispatch and unit commitment of hydrothermal systems require the coordinated use of different system elements in order to satisfy the system demand with the desired reliability levels.

5.6.1 METHODOLOGY

The model is based on the application of Linear Programming, Simulation and Dynamic Programming techniques to optimise the system operation. This approach is suitable for complex interconnected systems, which require efficient algorithms with regard to computer capacity and computational time.

The optimisation for every time step is achieved through a primal network algorithm which considers available water for the hydro plants and available fuels for the thermal plants. Upper and lower limits are implicit parameters in the computations. An efficient iterative procedure is used to account for non-linearities. Convergence is ensured and achieved after a few iterations.

The optimum economic dispatch is obtained through the application of the primal network algorithm. Simulation is used to assess the release of available spinning reserve of the units and the required load shedding caused by the tripping of the largest unit in operation (n-1 criteria). The process is repeated for every time step until the established reliability levels are achieved. Dynamic Programming is applied to account for start-up and shutdown costs of thermal units.

Stepwise procedure
Step 1 - Base case:
Establish overall minimum system operation cost considering only physical constraints

Step 2 - Reserve requirements:
Determine overall minimum operation costs adding reserve requirements

Step 3 – Start up and shut down costs:
Determine overall minimum operation costs adding start up and shutdown costs

5.6.2 INPUT DATA

The data requirements of WHTEDUC comprised both fixed parameters which define the physical characteristics of the system (fixed data) and information, which varies with time (variable data).

FIXED DATA

The fixed information comprises following information:

Total system:
- Number of hydro plants
- Number of thermal plants
- Number of stages in load shedding scheme
- Critical stage in load shedding scheme

Hydro plants:
- Number of units
- Operational limits of each unit, in MW
- Maximum water consumption/unit
- Inertia constant of turbo-generator unit
- Production curves, in the form of elevation-unit water consumption-output functions
- Characteristic function of spinning reserve availability
- Characteristic function of spinning reserve release

Thermal plants:
- Number of units
- Operational limits of each unit, in MW
- Number of fuels consumed, maximum 2
- Fixed and incremental cost constants
- Start-up and shut down costs
- Inertia constant of turbo-generator unit
- Characteristic function of spinning reserve availability
- Characteristic function of spinning reserve release

Load shedding scheme:

- Under-frequency (U-F) level
- Gradient of frequency drop
- % of system load shed
- Time delay
- Feeders connected to the U-F relay

VARIABLE DATA
The variable data is given for every day and remain constant for the 24 hour period.

System demand:
- Forecasted hourly power demand over 24 hour period

Hydro plants:
- Availability of units
- Must-run units
- Water volume available for 24 hour period

Thermal plants:
- Availability of units
- Must-run units
- Fuel cost
- Fuel availability over 24 hour period

Water volume available for each hydro plant should be determined in the context of an overall water management policy, which can be achieved through a program such as HYDOP.

5.6.3 RESULTS
WHTEDUC provides following information:

- Expected hourly production of the hydro and thermal stations in the system
- Deficits due to unsatisfied power demands
- Hourly reserve available
- Hourly output of every thermal plant for each fuel type used
- Operation cost of every thermal plant
- Total water used by the hydro plants

Sample results are presented in Fig. 5.22.

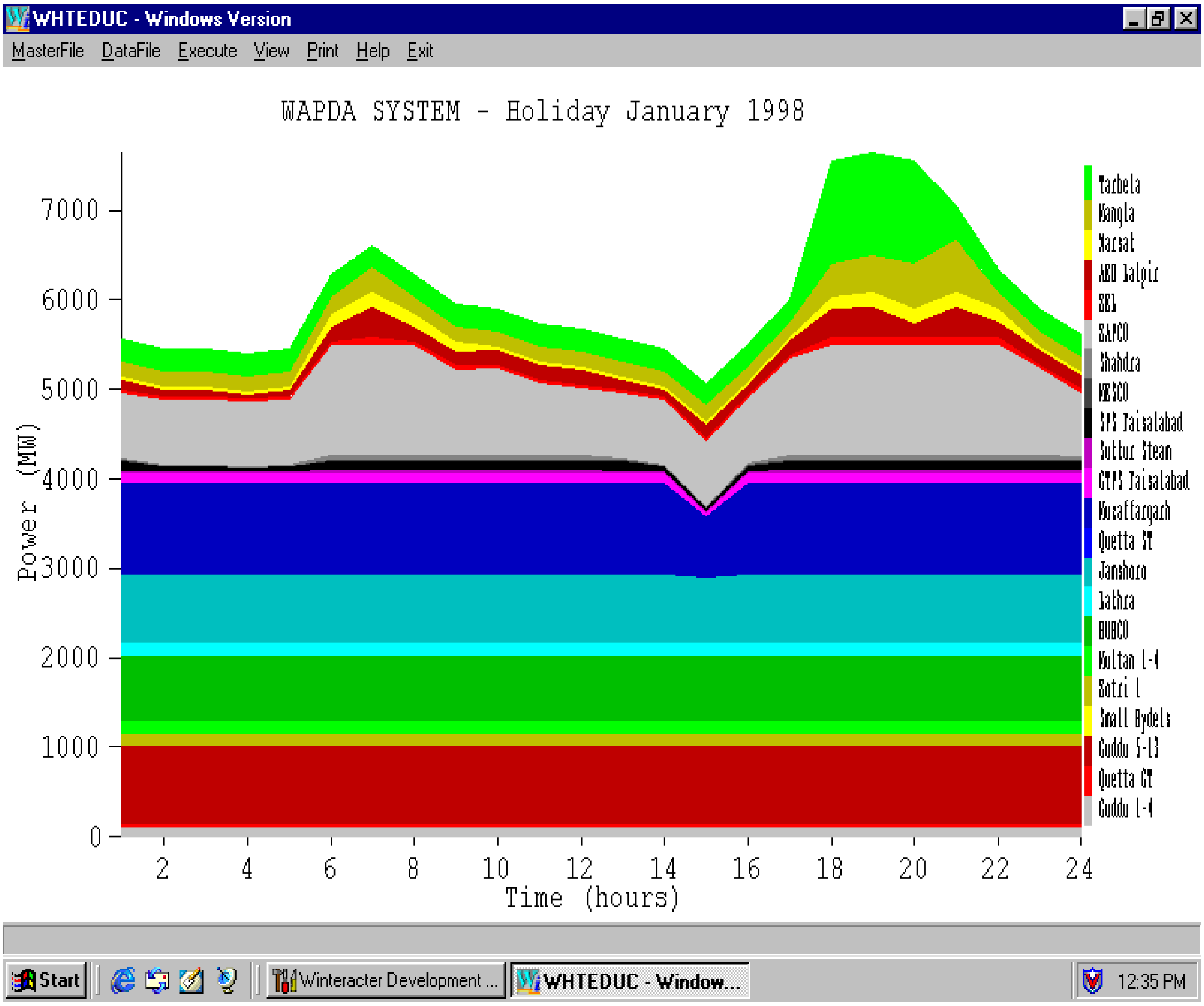


Fig. 5.22: **Sample output**

6. DETERMINATION OF SRMC AND LRMC

Project layout and design requires the determination of marginal costs short- and long-range (SRMC and LRMC). These parameters are determined on basis of the expected future development of the interconnected electric system.

SRMC are determined on basis of production costs and are routinely calculated for dispatching purposes. These vary with the type and availability of generating units, season, time of day, hydrologic conditions, etc.

LRMC are affected by production costs and depend on the foreseen expenditures associated with capacity additions required to cover the forecasted demand. The time horizon may extend over 1 or more decades.

Appendix “Economic Appraisal Criteria for Electric Power Projects”(KfW, April 1994) and Appendix “Guidelines for Marginal-Cost Analysis of Power Systems” (World Bank, Energy Department, Paper No. 18, June 1984) gives some background on the subject and describes procedures to determine marginal costs.

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