Chapter 2

Generator Maintenance Scheduling

Generators in the electrical power system should be maintained regularly at appropriate period so that the generator can work properly and its serviceable life can be prolonged. Thus it will result in an efficient electricity generating system as a whole. There are normally numerous generators in each electrical power system and each one of them needs periodically preventive maintenance, annually or monthly. So the maintenance scheduling of these generators is very important for electricity production. Therefore, it should be carried out in such a way that it is most cost-effectiveness to the responsible organization's operation.

2.1 Objective of the Maintenance Scheduling

For general electrical power system, planning always has two main objectives namely economics and reliability. Economic objective normally focuses on the operation which generates maximum benefits or minimizes its total production expenditures. The power system reliability which should be in acceptable and appropriated criteria; practically the electricity regulator usually determines the standard reliability indices. Hence the determination of preventive maintenance schedule is to find the optimal or tradeoff between the economical and the reliability objectives.

2.1.1 Economic Objective

In general business, the economical objective is related to company's benefit; it is not different in electricity industry. The benefit is calculated from income and expenditures. In an isolated power system that has income from certain electricity tariff; the economic objective can be achieved by minimizing production expenditure. The major hydro power system is different because of an uncontrollable factor of this system which is the water inflow that comes from the nature. Then, the system must have the interconnection with other for exporting the excess energy especially in the wet year and importing the shortage energy especially in draught year. When two systems are controlled, the export and import energy prices are set based on economical concept. Different between export and import tariffs are dependent on time of day and day of year. The economic factor of a power system can be classified as follows;

- System Incomes

Main income of the system is electricity selling that is classified to customer and neighboring system. Assume the electricity tariff to the customer is certainly determined by the regulator, and then it will be neglected in economical factor calculation. The quantity of customer demand is still taken into account for calculating the export and import power. The exported income is different because the system operator can control the exported quantity and time. If system exports in proper time with optimized power, the income will be the highest.

- System Costs

Many costs are considered for a power system. The first is generator operating costs that are separated to fixed and variable cost. Fixed cost is the cost that is not changed, when the generated energy increase or decrease such as personnel wages or administrative expense etc. Variable cost concerns the cost in the opposite side, such as fuel cost or variable operation and maintenance expenses etc. Then only variable cost will be considered in the maintenance scheduling problem. However, the fuel cost is not determined for any hydro unit which is very low when comparing with major expenses or incomes.

Next is the imported cost, because the imported power and time can be controlled. Then this cost must be considered. If the system imports power in low imported price period with proper quantity, the cost will be minimized. Moreover, the maintenance cost which includes expenses used for all equipment maintenance related such as lubricants, coolant, and personnel who operate maintenance is considered. They will be taken into account when maintenance planner plans scope of work and roughly period. However, the scope of work and roughly period will be given to system planner as an outage requirement, then it can be neglected in the maintenance scheduling problem.

The last cost in power system management is outage cost that is the economical impact to customers such as material damage, loss of opportunities etc. The system planner must determine the expected unserved energy before the outage cost can be calculated later. However, the system operator can re-schedule the shutdown program when the system has more risk outage problem. That means the maintenance schedule will be reviewed for increasing the system reliability when uncertain factor impact. When comparing with the computation time of expected unserved energy and re-schedule capability, this cost can be neglected.

Concern to the many kinds of income and cost, the equation 2.1 will be written.

$$Maximize\left(Income_C + Income_E - Cost_G - Cost_I - Cost_M - Cost_O\right) \qquad (2.1)$$

When some income and costs are neglected as described above, the equation will be reduced to new one that is shown in equation 2.2.

$$Maximize(Income_E - Cost_I) \qquad (2.2)$$

Where, $Income_C$ is the income of electricity selling to customer

$Income_E$ is the income of electricity selling to neighboring Systems.

$Cost_G$ is electricity generating costs.

$Cost_I$ is electricity import costs.

$Cost_M$ is maintenance costs.

$Cost_O$ is outage costs.

When the economic is employed as major objective, the system incomes and costs must be calculated, and then the production planning has to be completed. The methodology of production planning will be used with consideration of planning details and computation time because the generator maintenance scheduling problem is a long-term operation planning, the consideration period may be more than one year. Many uncertain factors will impact to the plan, and then if the plan is planned in detail, the computation time is long when concern to the plan will be changed much in the future. The several methodologies of maintenance scheduling problem will be described later.

2.1.2 Reliability Objective

At present, the reliability index of the electrical power system comes out of the probability criteria such as "Loss of Load Probability"(LOLP) index, "Expected Unserved Energy" (EUE) etc. Because of their quantitative displayable indices [2] so the method used for planning of generators maintenance has to apply the indices derived from the probability criteria.

Such indices consideration may be divided into two levels. The first level is the one that has reliability index within the standard criteria which may consider it as a significant constraint in the plan determination. The second level is the one which is the best reliability index. However in practical, the first level would be principally considered while the second one would be used for integrating consideration with the economic objective such the way that how to optimize the solution whereas the variables used for such consideration in the optimization problem would depend upon the priority weight given to both objectives by the determiner of such generator maintenance schedule which will be describe in the next topic.

2.2 Generator Maintenance Scheduling Method.

In the generator maintenance scheduling problem; various principles are used in order to obtain the generators maintenance schedule that satisfies both reliability and economic objectives. The principal variable selected to use for either type of electrical power system would depend on the system reliability criteria and the costs spent for planning as well as the purposes of that system planning.

In the past, the indices of the system reliability came from the "Deterministic Criteria" which the value was relatively displayed for a considered system, a power system with its 10 % reserved capability would be more reliable than with only 8 % reserved, but it could not be identified how much or how many the betterment was. Hence, in determination the planning how to maintain generators workability, the reserve capacity is the main variable in the consideration which originates methods of "Levelized Reserve" and "Levelized Reserve Rate"

Later on, the system reliability indices, for example, LOLP, EUE were always applied in displaying the system reliability. The indices are based on probabilistic criteria and can show more accurate quality of reliability. Then, they can be used as the objective variable. The LOLP will give generator maintenance schedule that emphasizes mainly on the system reliability but the EUE method will yield the energy expected not to supply to some users so in such consideration, there should be arrangement of generators capacity series. If the serial gradation is made upon the productive expenditures basis, it is called EUE value which becomes the value summation with both economic and reliability aspects together, the EUE value is then brought for the solution and these are the Levelized LOLP and Levelized EUE methods.

Since bringing EUE in the procedure as the main variable in the solution is bringing the energy data in the calculation, the result would be as if the expenditures in production are only calculated but in fact there are other economic costs such as loss when the generating capacity is reduced i.e. the “Outage Cost”. If these expenses are also brought into account, we would be able to identify the whole expenditures for the energy production which is so called “Energy Cost”. Hence the possible generators maintenance schedule would come out to match more the economic requirement, however which index is the most appropriate to use as the main variable depends upon that electrical system type what it wants generators schedule to look like.

2.2.1 Maintenance Scheduling by Levelized Reserve Method.

This method would bring the power reserved capacity obtainable from calculation as in equation 2.3 [2,7] of the system to be the principal variable. Shutdown unit for maintenance in the system is the reduction of the reserved capacity at the maintenance interval, so the most appropriate time or position to stop to do such operation is when the whole system has maximum reserved capacity, that is the effort to reduce the magnitude of reserved capacity or at the peak point and the best solution is at the case the reserve or electricity reserved rate in every fractional interval having equal magnitude. In other words, it is the time when the standard deviation of the electricity reserve, or its rate, is at the lowest value.

The consideration in how to select the power reserve or the energy reserve rate as the target of determination of the maintenance schedule will be related to the electricity system administration. If the determination of the power reserve calculated from the biggest generator of those in the system, the desirable reserve in each fractional interval would be constant. The determination of the maintenance plan should use the power reserve as the target or pivot variable. If the determination of the power reserve is proportional to the power load magnitude, the target variable used should be the power reserve rate.

The aim of determining a maintenance plan with such principle is how to make the electricity reserve or the power reserve rate in every successive interval have equal value which can be obtainable as derived in equation 2.3 and 2.4 [7]

$$R(t) = \sum_{j=1}^{n} P_j\left(1 - X_j(t)\right) - P_L(t) \tag{2.3}$$

$$R_r(t) = \frac{R(t)}{P_L(t)} \tag{2.4}$$

$$R(1) = R(j) = R(j+1) = R(T) \tag{2.5}$$

$$R_r(1) = R_r(j) = R_r(j+1) = R_r(T) \tag{2.6}$$

Where, $R(t)$ is the power reserve of system at the time interval t

$R_r(t)$ is the power reserve rate of system at the time interval t

P_j is the size of the generator j

$X_j(t)$ is the state variable of generator j at the interval t (If available =0, outage $=1$)

$P_L(t)$ is the expected load at the interval t

n is the total number of generators

T is the total number of intervals

The procedure of this method is started firstly by arranging the order of generators in the system normally from largest to smallest ones. The largest generator always affects a greater deal to the system, so it must be considered first. Hence, such levelized reserve method is usually discovered to give yield rather concisely responding to the reliability objective of the system.

2.2.2 Maintenance Scheduling by Levelized LOLP

LOLP is the index that indicates the load outage probability. LOLP value can be found from the equations 2.7 and 2.8. The generators maintenance scheduling that the power system must give the lowest total LOLP (calculated from averaging each LOLP in every fractional interval). When the consideration starts from the no maintenance outage, each outage will result in higher total LOLP, so the problem is how to minimize the final LOLP.

At the interval that LOLP index is highest, it is also the peak load time, then the most appropriated period for maintenance should be considered at the lowest load time or at the lowest LOLP index. The target of this method is how to try to make LOLP of each interval have equal or nearest values to each other that would eventually also result in the lowest total LOLP. The procedure of Levelized LOLP principle is illustrated in Figure 2.1 [2,7]

$$LOLP = \frac{\sum_{k=1}^{m} p_k t_k}{T} \tag{2.7}$$

$$LOLP = \sum_{k=1}^{m} \left(P(L_k) \times p(L_k) \right) \tag{2.8}$$

Where, p_k is the individual outage probability at load level *k*.

t_k is the sum of tome interval at load level *k*.

T is total consideration period.

$P(L_k)$ is the cumulative outage probability when the load is equal to L_k.

L_k is the equivalent load level k.

m is the total number of equivalent load level.

$p(L_k)$ is the individual probability that the load is equal to L_k.

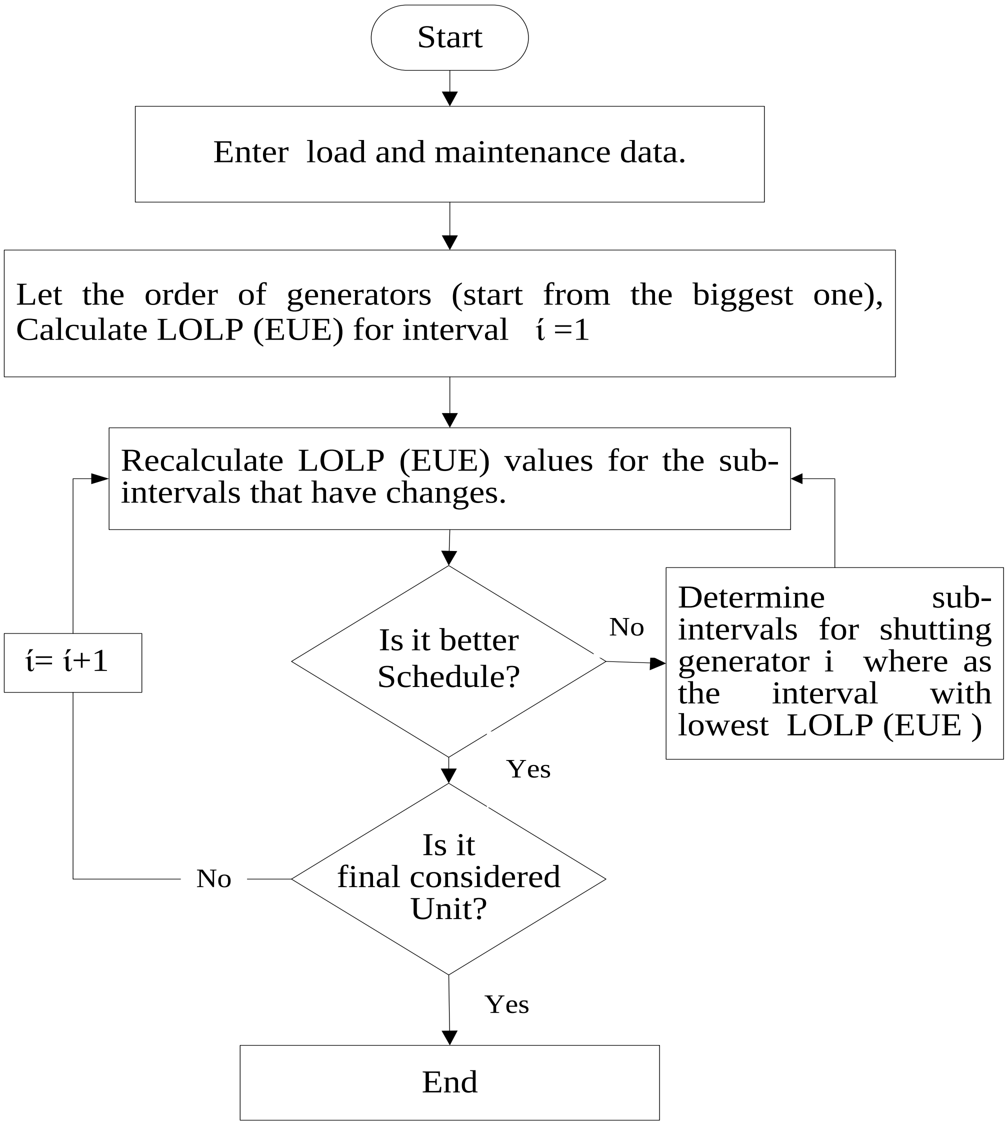


Figure 2.1 Algorithm of Levelized LOLP and Levelized EUE

2.2.3 Maintenance Scheduling by Levelized EUE

EUE is the expected unserved energy to the customer after all generators have been calculated following the order. The principle of the solution by this method is the target to have each generator outage for maintenance at the time it cannot supply the smallest energy to the customer by adding each generators into the system and select the sub-interval with lowest EUE. It has procedure of solution similar to those of Levelized LOLP method as shown in Figure 2.1

2.2.4 Maintenance Scheduling with economical objective

As described before, the objectives of power system management are reliability and economic. In general, both of them cannot be achieved at the same time. Practically if one is employed as objective function, another will be treated as a constraint. Usually economic is objective function because the electricity still be the infrastructure for life qualities of people, businesses and industries. To guarantee the qualities of supply, the electricity regulator will set the minimum reliabilities such as minimum reserve, securities criteria etc. In the system operation, the minimum operating reserve and standard securities constraint will be determined. The system generators and operational planner must meet these standards before minimizing system cost or maximizing system profit.

In the topic 2.1.1 these described about factors of economical objective for a major hydro power system. The equation 2.2 can be expanded to equation 2.9.

$$Maximize\left(\sum_{t=1}^{T}\left(Rex_t \times Pex_t\right) - \sum_{t=1}^{T}\left(Rim_t \times Pim_t\right)\right) \tag{2.9}$$

where ; $Rex_t = \text{exported tariff at time } t$

$Pex_t = \text{exported Power at time } t$

$Rim_t = \text{Imported tariff at time } t$

$Pim_t = \text{Imported Power at time } t$

$T = \text{Total time}$

The maintenance scheduling with economic objective can be done by testing the feasible schedule with reliabilities constraint before calculating the system cost and profit. After that the lowest cost or highest profit with reliability constraint will be selected. The algorithm of this concept is shown in figure 2.2

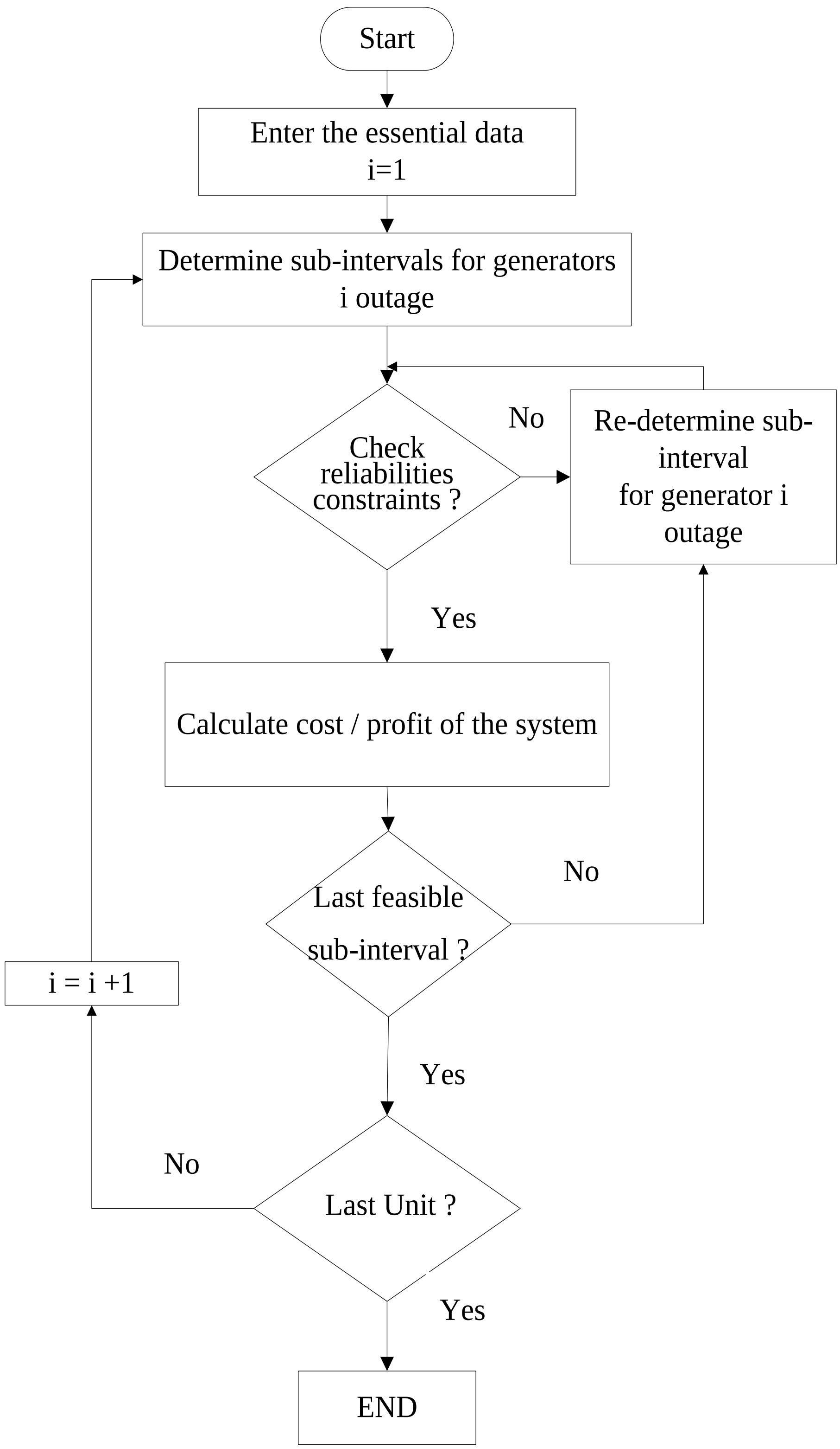


Figure 2.2 Algorithm of maintenance scheduling with economical objective

2.3 Constraints

In operational planning of a power system, there are two major objectives, namely, economical and reliability ones, however under such requirement and methodology constraints, there are also many other concerned factors. They are the period or time interval needed for the maintenance operation, limitation due to personnel and equipment needed in such sub-interval, and condition due to the systematic scenario reliability, etc. The conditional details which effect planning of generators maintenance can be concluded as follows:

2.3.1 Maintenance Stage Constraints [2]

In practical, the operator who is responsible for the operation and maintenance of each generator shall notify other colleagues about the period needed to perform the maintenance, because each generator has its own specific operation, different running and shutdown for maintenance individuality. If the maintenance is done before its optimum period, it will result in some previously changed accessory parts have not been used cost-effectively to its maximum utility. But if the maintenance is delayed after its optimum period, some parts may be worn out and may consequentially cause severe damage to the system. Such time-frame constraint can be formulated in the following equation, namely;

$$ML_j \leq i_j \leq MH_j \ , \qquad (2.10)$$

where as

i_j is the sub-interval of operation stop for generator j maintenance.

ML_j is the first sub-interval of operation stop allowed for generator j maintenance.

MH_j is the final sub-interval of operation stop allowed for generator j maintenance.

2.3.2 Continuity of Maintenance Activity [2]

In whichever generator to have maintenance, it needs a period of continuous time for operation, namely, the maintenance period of a generator has to be continuous accordingly to a determined time interval which can be shown in the following equation:

$$LT_j - ST_j + 1 = MT_j \qquad (2.11)$$

Where; LT_j is the final sub-interval that the generator j is outage

ST_j is the first sub-interval that the generator j is outage

MT_j is the maintenance time requirement for generator j

2.3.3 Crew Constraints [2]

In practice, the actual maintenance shall not limit to any certain generator but many generators may have simultaneously maintenance. If too many personnel and equipment are prepared, even though the many generators maintenance can concurrently performed, it is extravagant in administrative point of view since the costs have to spend beyond necessity and the capacity of crew and equipment at concurrent maintenance is always limited. Hence, if too many generators are outage for maintenance beyond the available crew and equipment capacity, such maintenance shall not only be useless but it also reduces the system reliability, the equation that shows the constraint is:

$$\sum_{j=1}^{n}\left(X_j(t)V_k\right) \le V_r \tag{2.12}$$

where

V_k is the number of maintenance crew working on unit j.

V_r is the total number of maintenance crew.

$X_j(t)$ is the state variable of generator j at the interval t (If available =0, outage $=1$).

2.3.4 Multiple Times of Maintenance [2]

For a generator, there may be many parts which do not need concurrent maintenance at the same time, for example, in gas turbine generators, no matter they work independently or work with the thermal power plants, they need maintenance when their number of serviceable hours have come to due which the certain hour may also depend upon the magnitude of the supply load, so it is possible that some generators need to outage in order to have maintenance more than once within the considered periodic cycle. Such constraints are shown as in equations 2.13 and 2.14 which show the shortest period between maintenance due time and the next one, in doing so would avoid too short operational period.

$$\sum_{j=1}^{n} X_j(t) = MT_{j1} + MT_{j2} \tag{2.13}$$

$$ST_{j2} - LT_{j1} \ge B_j \tag{2.14}$$

where;

MT_{j1} is the time used for maintenance generator j for the maintenance time No.1.

ST_{j2} is the initial sub-interval used for maintenance generator j for the 2nd time.

LT_{j1} is the final sub-interval used for maintenance generator j for the 1st time.

B_j is the shortest time needed between adjacent maintenance time for generator j.

2.3.5 Minimum Reserve Capacity [7]

In management of electrical power system, it must provide the reserving power sufficiently to cope with any contingent emergency that may abruptly reduce the regular power supply. In general, the minimum reserve can be determined by two characteristics, namely:

a. Determine in percentage in harmony to that moment load as in equation 2.15 and

b. Determine the reserve according to m number of the biggest generators or imported transmission circuit as in equation 2.16.

$$\sum_{j=1}^{n} P_j X_j(t) + I_{\max} - P_L(t) \geq \frac{R_r(\min)}{100} \times P_L(i) \qquad (2.15)$$

$$\sum_{j=1}^{n} P_j X_j(t) + I_{\max} - P_L(t) \geq 1^{st}(P_j) + 2^{nd}(P_j) + \ldots + m^{th}(P_j) \qquad (2.16)$$

where; 1^{st}, 2^{nd},…,m^{th} are running unit numbers that is sorted by descending unit capacity.

n is the total number of generators

P_j is the capacity size of generator j

$P_L(t)$ is the forecasted peak load at the time interval t

$R_r(\min)$ is the lowest acceptable reserve (percent)

$m^{th}(P_j)$ is the power capacity of the last unit or circuit when use m biggest generators or imported transmission circuits to determine the minimum reserve requirement.

$I_{\max}$ is maximum imported ability

2.3.6 Reliability Index Criteria

In general, the organization that is the electrical power supply regulator shall determine the worst reliability index as the criterion in planning the generator maintenance. The final outcome plan must yield the reliability indices to a certain criteria which are shown as the following equation:

$$\frac{\sum_{t=1}^{T} LOLP(t)}{T} \leq LOLP_{\max} \qquad (2.17)$$

where

$LOLP_{\max}$ is the maximum LOLP index determined by the electricity regulator

$LOLP(t)$ is the LOLP index at a sub-interval t

T is the total number of intervals within the considerable period.

2.4 Searching Techniques

The methodology in maintenance scheduling problem is a kind of optimization problems, because many possible maintenance schedules will be selected. The best schedule is different when the objective function is different, and also may be slightly different if a different searching technique is employed. Some can give the global best solution, but take more than acceptable computation time in real operation; some use lower computation time but may give non-global best solution. However, when concern to the uncertainties, the proper searching techniques will be selected depend upon the size of the problem, accuracy and computation time.

2.4.1 Complete Enumeration Method [7]

This method includes the consideration of all feasible cases, then selected one with the best objective function value because any possible schedules are considered, the result is guaranteed to be the best schedule. With this concept, the computation time is very long, if n generators are considered for maintenance with k choices each, the 2^{nk} cases will be considered, however, the principle of such approaches can be improved in order to reduce the number of cases within consideration. This method is shown in Figure 2.3 and it is the example as the example 2.1. Example 2.1 from the figure 2.4 selects trajectory from point A to point J which has the shortest distance in total, the optimization method and its result is shown in table 2.1

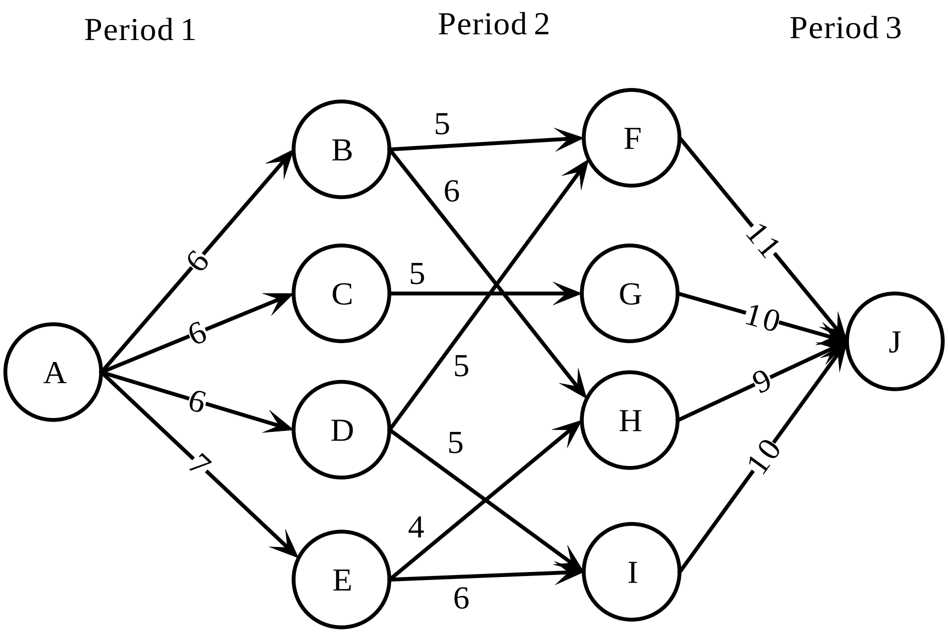


Figure 2.3 Problem case of the example 2.1

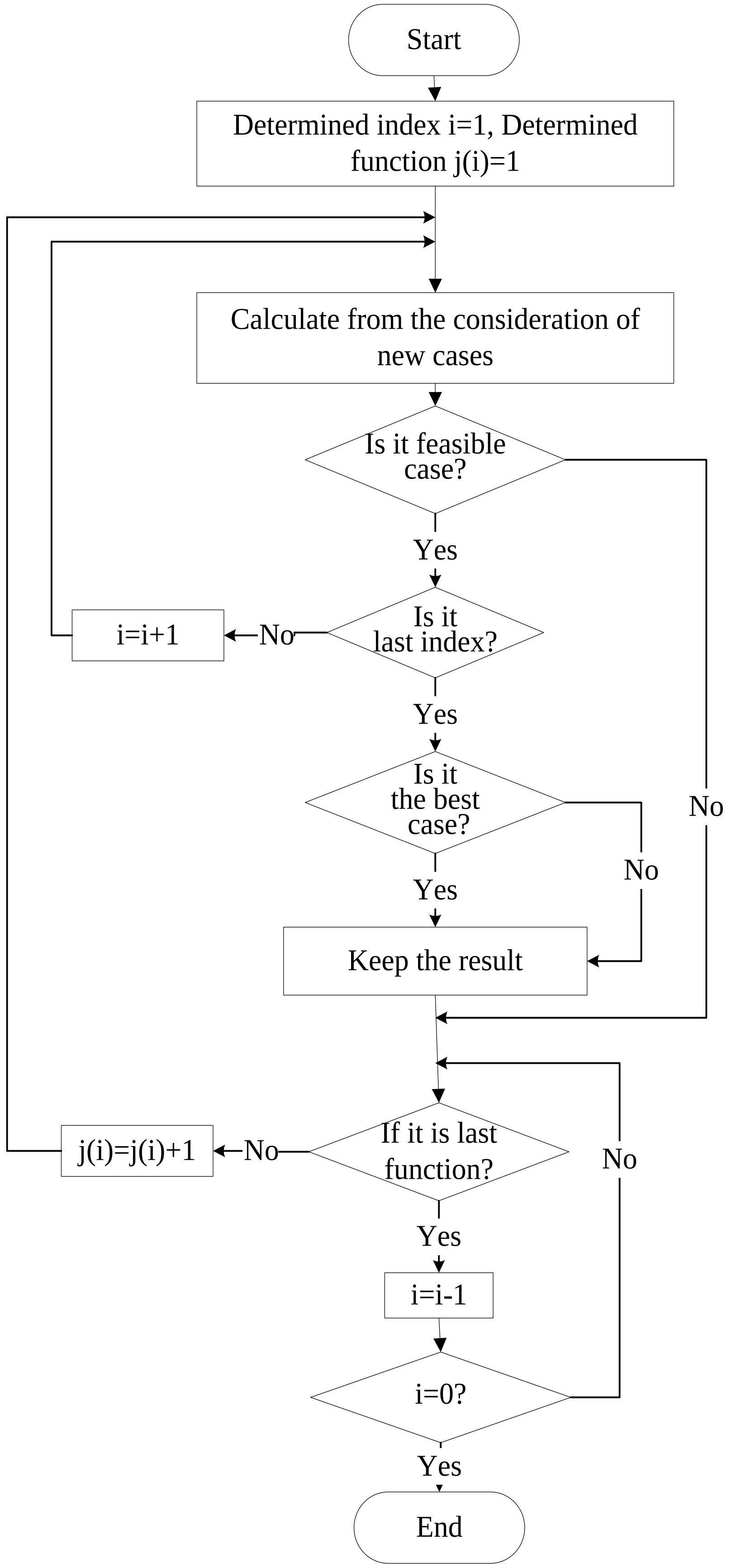


Figure 2.4 Complete Enumeration Method

Table 2.1 Solving process of the example 2.1

Stage	Variable1	Variable2	Variable3	Variable4	Possible Case	Trajectory in total	Result
1	A				Yes	0	
2	A	B			Yes	6	
3	A	B	F		Yes	11	
4	A	B	F	J	Yes	22	Yes
5	A	B	G		No		
6	A	B	H		Yes	12	
7	A	B	H	J	Yes	21	Yes
8	A	B	I		No		
9	A	C			Yes	6	
10	A	C	F		No		
11	A	C	G		Yes	11	
12	A	C	G	J	Yes	21	No
…							
17	A	D	F	J	Yes	22	No
…							
21	A	D	I	J	Yes	21	No
…							
26	A	E	H	J	Yes	20	Yes
…							
28	A	E	I	J	Yes	23	No

From the example 2.1, twenty eight cases have been considered, and the best solution has been found. However, it took long time due to consideration of many cases.

2.4.2 Dynamic Programming

Dynamic programming is a mathematical technique well suited for the optimization of multistage decision problems. This technique was developed by Richard Bellman in the early 1950s.

The dynamic programming technique, when applicable, represents or decomposes a multistage decisions problem as a sequence of single stage decision problems. Thus an N-variable problem is represented as a sequence of N single variable problems which are solved successively. In most cases, these N sub problems are easier to solve than the original problem. The decomposition to N sub problems is done in such a manner that the optimal solution of the original N-variable problem can be obtained from the optimal solutions of the N one-dimensional problems. It is important to note that the particular optimization technique used for the optimization of the N-single variable problems is irrelevant. It may range from a simple enumeration process to a differential calculus or a nonlinear programming technique.

Multistage decision problems can also be solved by the direct application of the classical optimization techniques. However, this requires the number of the variables to be small, the functions involved to be continuous and continuously differentiable, and the optimum points not to lie at the boundary point. The maintenance scheduling of generating units is a combinatorial problem. Therefore, there are several approaches for solving this problem. Dynamic, mixed-integer-linear, integer programming together with decomposition techniques have been combined with heuristics and intelligent system as the most realistic search method [3,13].

In this study, dynamic programming (DP) as search method is selected. It has been shown that the solution of maintenance problems by dynamic programming is appropriate due to the following reasons [2]:

a. DP is especially suitable for problems where a sequence of division is involved; maintenance problems belong to this problem category.

b. DP does not require that the objective function is a continuous function of decision variables and state variables, which conforms to the discrete characteristic of maintenance problems.

c. DP does not need the analytical form of the objective function and constraint functions. Only the objective function value at a given stage needs to be calculated. This feature of dynamic programming is very conductive to deal flexibly with many practical constraints of complex maintenance problems.

The DP method is amenable to application in more complex situations. Longer time steps make it useful to compute seasonal rule curves, the long-term storage plan for a system of reservoirs. Variable-head cases may be treated. A sketch of the type of characteristics encountered in variable-head plants is shown in figure 2.5. In this case, the variation in maximum plant output may be as important as the variation in water use rate as the net head varies. [18]

The equation 2.18 is used to clarify variable head hydraulic plant that is shown in figure 2.5.

$$q = q\left(p_H, \bar{V} \right) \tag{2.18}$$

Where; q is the hydro plant discharge rate,

$\bar{V}$ is the average volume used to present the effect of the hydraulic head,

P_H is the power output of each hydropower plant.

V_1, V_2, V_3 are the reservoir volumes number 1, 2 and 3 used to present the effect of the hydraulic head.

$MAX\ p_H$ is the maximum power output.

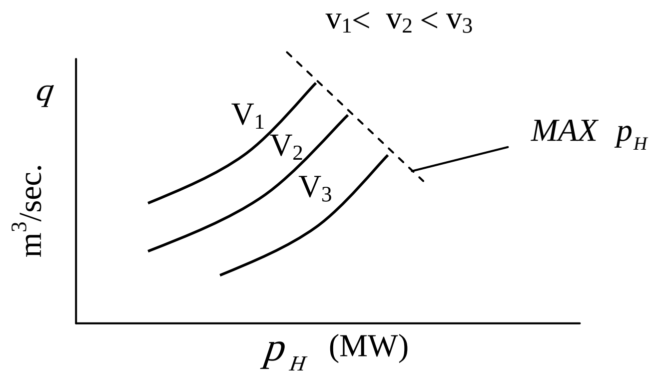


Figure. 2.5 Input-output characteristic for variable-head hydraulic plant

Suppose we are giving the interconnection system shown in Figure 2.6. We have the following hydraulic equations.

$$v_{1j} = v_{1j-1} + r_{1j} - q_{1j} - s_{1j}, \tag{2.19}$$

$$v_{2j} = v_{2j-1} + r_{2j} - q_{2j} - s_{2j}, \tag{2.20}$$

$$v_{3j} = v_{3j-1} + r_{3j} - q_{3j} - s_{3j}, \tag{2.21}$$

Where, $v_{(1,2,3)j}$ - Water volume in each plant,

$r_{(1,2,3)j}$ - Inflow to the reservoir of each plant,

$s_{(1,2,3)j}$ - Spill water from the reservoir of each plant,

$q_{(1,2,3)j}$ - Discharge through turbine of each plant.

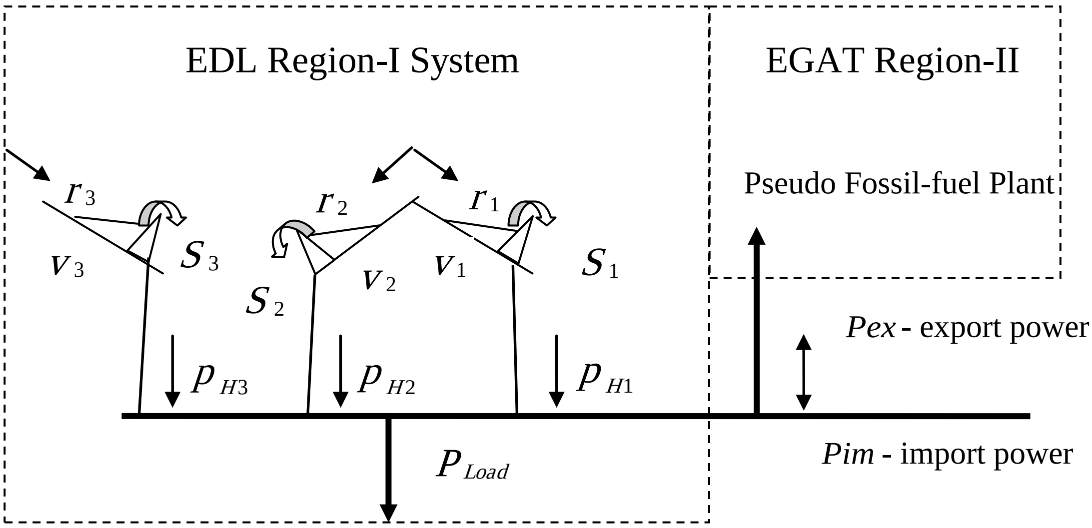


Figure 2.6 Interconnection system with hydraulically coupled hydroelectric plants

Similarly, we have the following electrical equation

$$P_{H1}\left(q_{1j}\right)+P_{H2}\left(q_{2j}\right)+P_{H3}\left(q_{3j}\right)+Pim_j-Pex_j-P_{Load\ \ j}=0 \qquad (2.22)$$

$P_{H(1,2,3)}\left(q_{(1,2,3)\ j}\right)$ - Power output and discharge through turbine of each hydro power plant during period j

Pim_j - Import power during period j ; Pex_j - Export power during period j

$P_{Load\ \ j}$ - Local load during period j

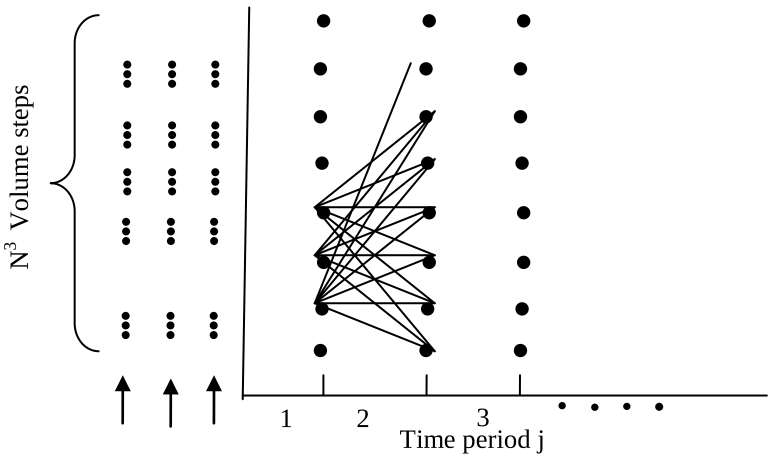


Figure 2.7 Trajectory combinations for coupled plants

There are a variety of ways to set up DP solution to this program. Perhaps the most obvious would be to again let the reservoir volumes, V_1, V_2 and V_3 , be the state variables and then run over all feasible combinations. That is, let V_1, V_2 and V_3 all be divided into N volume steps S_1, S_2 . . . S_3. Then the DP must consider N^3 steps at each time interval, as shown in Figure 2.7.

This procedure might be a reasonable way to solve the multiple hydro plant scheduling problems if the number of volume steps were kept quite small. However, this is not practical when a realistic schedule is divided. Consider, for example, a reservoir volume that is divided into 10 steps (N=10). If there were only one hydro plant, there would be 10 states at each time period, resulting in a possible 100 paths to be investigated at each stage. If there were three reservoirs with 10 volumes steps, there would be 1,000 states at each time interval with a possibility of 1,000,000,000 paths to investigate at each state.

This dimensionality problem can be overcome through the use of a procedure known as successive approximation. In this procedure, one reservoir is scheduled while keeping the other’s schedule fixed, alternating from one reservoir to the other until the schedules converge. The steps taken in the successive approximation method are shown as an example in figure 2.8 [18]

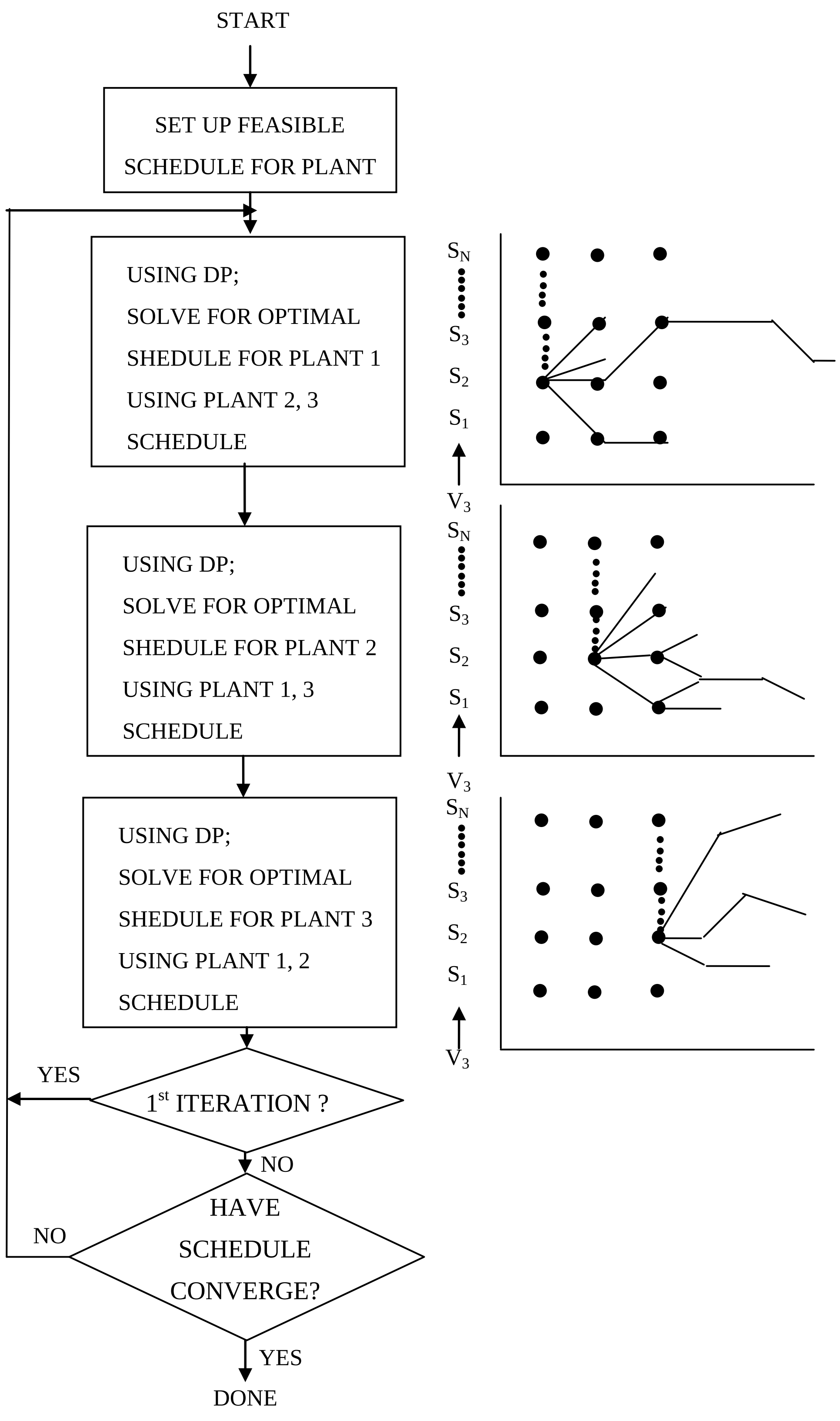


Figure 2.8 Successive approximation solutions

2.5 Reservoir Operation

The problem of water resource management is how the water in reservoir will be used efficiently. Generally, the reservoir operation planners employ the rule curve to control the usage of water in the reservoir to meet their purposes. Many kinds of rule curves will be select one or more depend upon the purposes of water in reservoir and the reservoir system in the river basin. In some places, the reservoirs are used for irrigation, electricity generation, flood control, transportation or pollution control and may be supported more than one purpose, or multipurpose. In some river basins, only one reservoir is in it, but may be multi-reservoirs are operated coordination both located as series and separated to each branch of the river. The scope of this study will consider only stand-alone reservoir in a river basin, and only electricity generation is supported due to the nature of Laos region-I reservoir.

To minimize the spill water, before starting of high inflow periods the reservoir storage should be at lower level in order to capture the incoming water and provide spill water protection. After the high inflow the reservoir should be ideally full for serving the demand. The inflow data that used for creating this curve is maximum inflow; the rule curve is the same concept of flood control rule curve and guarantees no spill water. Practically, if the maximum inflow will be used, the very high water will be released and brought the reservoir to more shortage risk situation. Then the inflow prediction for the rule curve is selected from high inflow that lower than maximum up to the acceptable spill probability such as once in decade, once in five years etc. Concern to the electricity generation reservoir and spill water protection, the water can be released pass turbines in the same time that high inflow coming, if assume flood problem is not concerned. Normally, the reservoirs will employ this rule curve as maximum limit, called upper rule curve, and Figure 2.9 shows this rule curve.

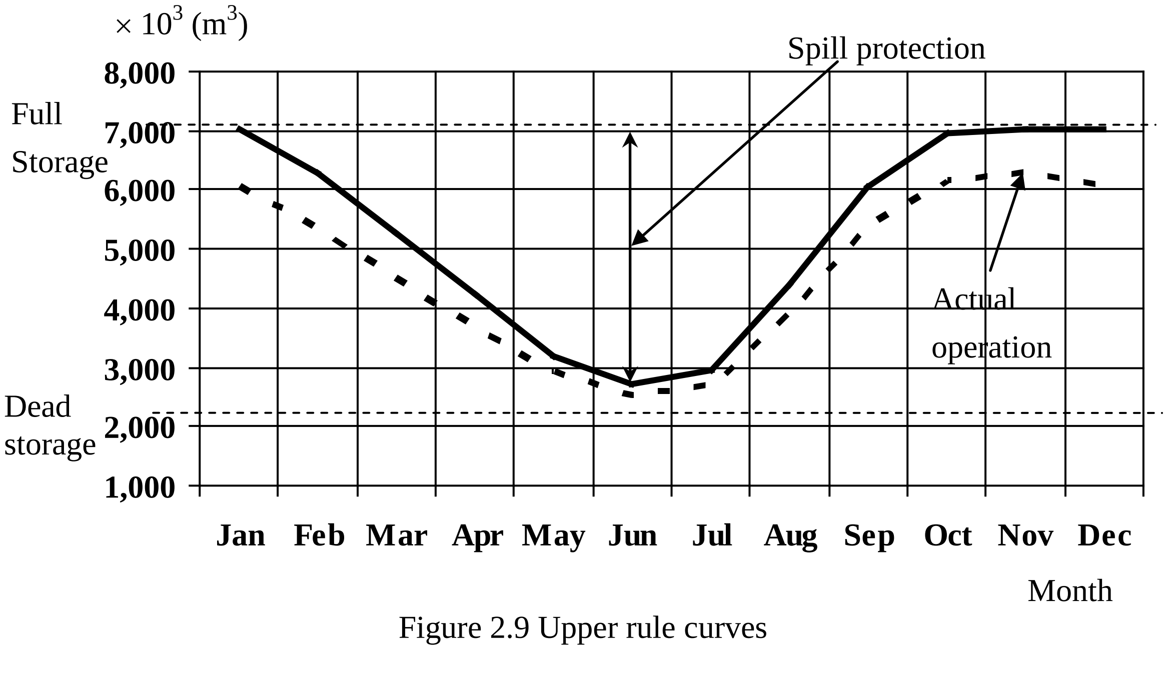


Figure 2.9 Upper rule curves

On the other hand, the system requires minimum generation from the hydro power station that implied the system require minimum water storage for electricity generation. For water shortage protection, the minimum limit called lower rule curve must be calculated. The release water is easy to calculate from minimum generation but the inflow is more difficult to determine. If the minimum inflow is used, it will guarantee the water shortage. If the higher inflow is employed, the system will take higher risk. However, it will give more opportunities to produce the electricity at the most proper time. The proper inflow, that will be used to create the minimum limit, is dependent upon the acceptable water shortage probability, the consequential damage from water shortage and the opportunities to release electricity shortage. If the reservoir is very large when compared with the inflow, in this situation, the minimum inflow should be selected because it guarantees that electricity shortage will not occur as the reservoir has large storage capability. The example of minimum limit is shown in figure 2.10.

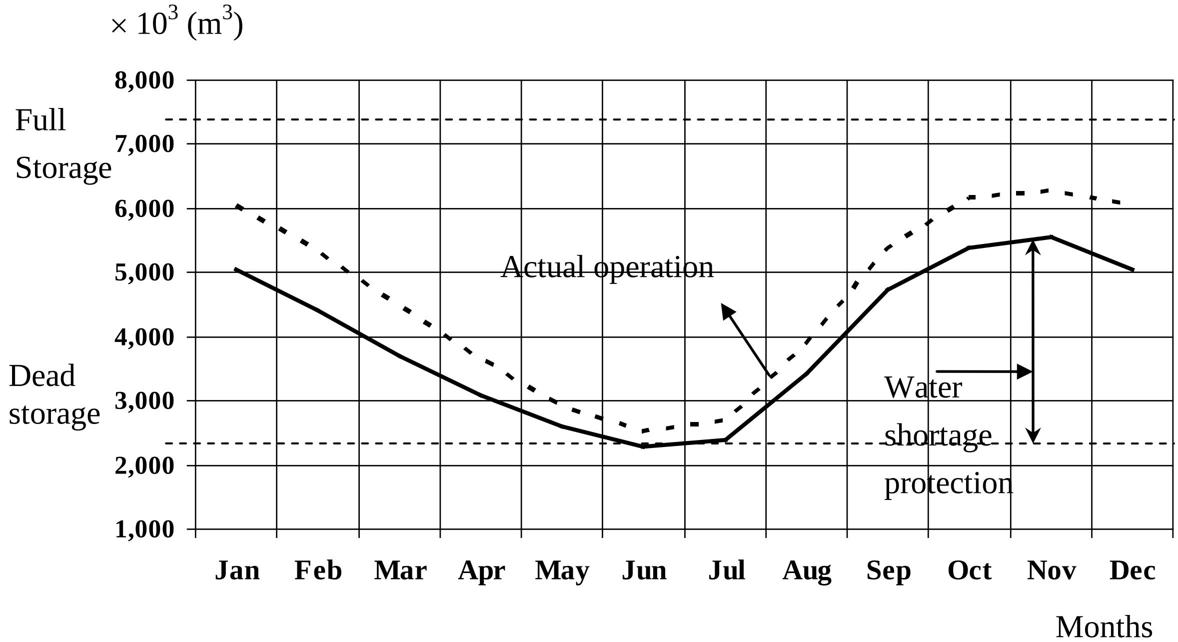


Figure 2.10 Lower rule curves

2.6 Hydro System Production Planning

In the general system, many kinds of power plants and many types of used fuel are employed. The hydro power plant has different characteristics especially variable cost because hydro does not have certain fuel cost, that normally is the majority cost of power generation. The problem is optimum dispatch for hydro generating unit and gives the best economical objective for the system. If the water value is assigned as the replaced generating unit fuel cost, that can imply short run marginal cost, the water value should be maximized. Generally, the short run marginal cost will be high during the peak period of system and will be low during the off-peak period. The concept of peak shaving method, as described in section 2.7, can be used to manage hydro generation. However, with peak shaving method, the minimized cost of the system is not guaranteed. More complex method such as hydro-thermal coordination with optimization techniques is used. The summary of hydro-thermal coordination is described in section 2.8. For a pure hydro power system, which does not have other types of power plant in the system, the methodology must be adapted. Short run marginal cost must be changed to exported and imported price as water value reference. The detail of this method will be explained in Chapter 3.

2.7 Peak Shaving Method

Peak shaving method is the consideration of hydropower to generate at peak hours due to the highest marginal cost. In which expected capacity of hydro generating unit can be calculated by an algebraic equation 2.23, and can calculate the total energy in which expected hydro generating unit can generate at k load level from equation 2.24 [7]

$$C_e = \sum_{i=0}^{N-1} C_i P_i \,, \tag{2.23}$$

$$E_k = P(L_k) \times T \times C_e \,, \tag{2.24}$$

where, C_e is the expected capacity of hydro generator.

C_i is the generating capacity at power level i.

P_i is the probability of generating at power level i.

N is the number of generating power levels of the generating unit.

E_k is the electrical energy generated at load level k by the generator at generating power level i.

L_k is electrical demand at load level k.

$P(L_k)$ is cumulative probability of the electrical demand which is grater or equal to load level k.

T is total consideration time.

From the equation 2.23 and 2.24, the electrical power that hydro generating unit can generate not more than the maximum generating at the highest Generating Power Level, as load level of hydro generating unit which can distribute to maximum but not more than the setting energy as shown in equation 2.25 [4]

$$L_{cr} = \min\left(L_k : E_k \le EEU\right), \tag{2.25}$$

where; L_{cr} is a suitable load level to be supplied by a hydro generating unit.

EEU is the limited energy quantity of a hydro generating unit.

2.8 Hydro-Thermal Coordination [18]

The hydrothermal Coordination is usually more complex than the scheduling of an all-thermal generation system. The reason is both simple and important. That is, the hydroelectric plants may very well be coupled both electrically (i.e. they all serve the same load) and hydraulically (i.e. the water outflow from one plant may be a very significant portion of the inflow to one or more other, downstream plant).

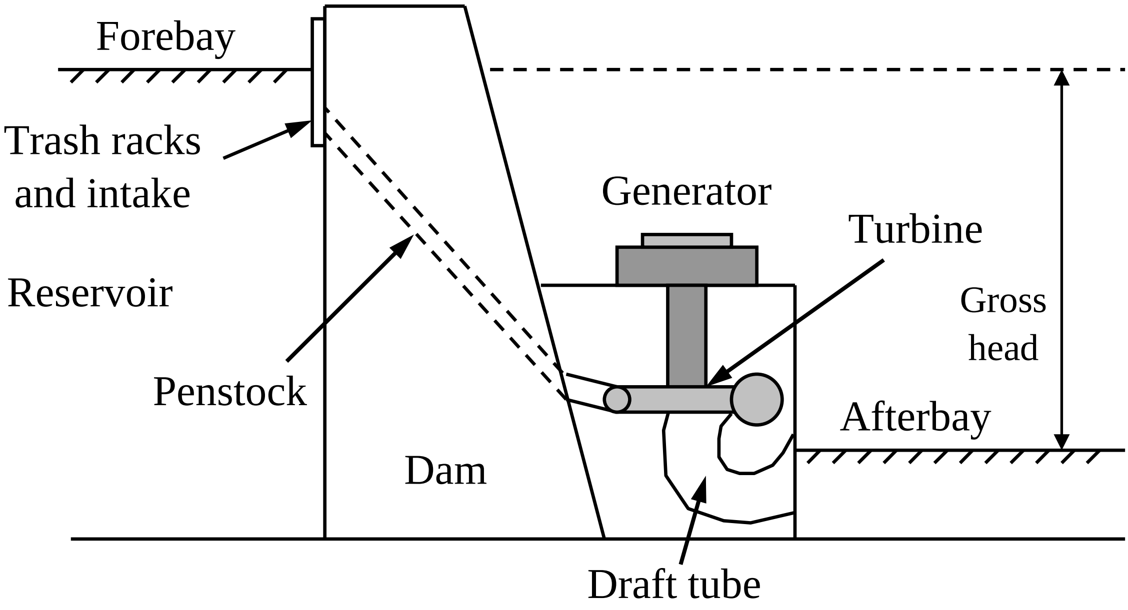
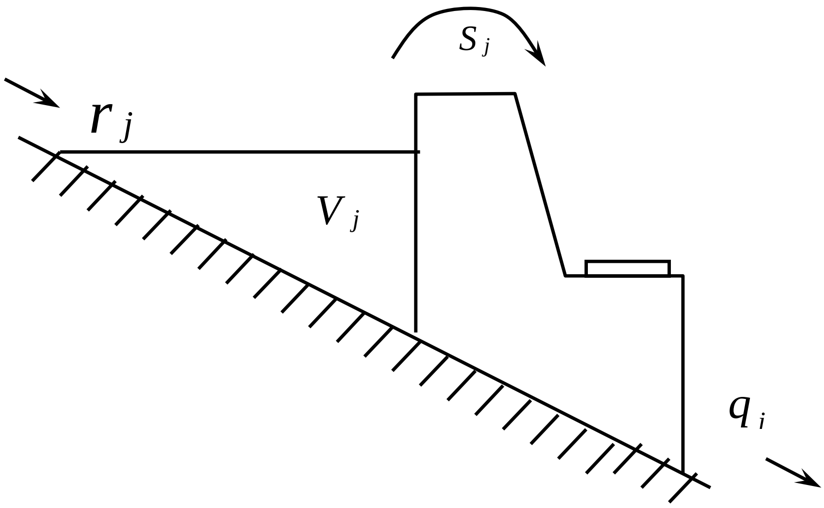


Figure 2.11 Hydroelectric Plant components

No two hydraulic systems in the world are alike. They are all different. The reasons for the differences are the natural differences in the watersheds, the differences in the manmade storage and release elements used to control the water flows, and the very many different types of natural and manmade constraint imposed on the operation of hydraulic system. The hydroelectric plant is illustrated in figure 2.11.

The coordination of the operation of hydroelectric plants involves, of course, the scheduling of water releases. The scheduling is normally divided into Long-Range Scheduling and Short-Range Scheduling. Long-range scheduling typically goes from one week to one year or several years. For hydro schemes with a capacity of impounding water over several seasons, the long-range problem involves meteorological and statistical analyses. Short-range hydro scheduling (1 day to 1 week) involves the hour-by-hour scheduling of all generation on a system to achieve minimum production cost for the given time period. In such a scheduling problem, the load, hydraulic inflows, and unit availabilities are assumed known. A set of starting conditions such as reservoir levels is given, and the optimal hourly schedule that minimizes the desired objective, while meeting hydraulic system, and electric system constraint, is sought. Part of the hydraulic constraints may involve meeting "end-point" conditions at the end of the scheduling interval in order to conform to a long-range, water release schedule previously established. The short-term hydrothermal scheduling problem is a basic and general method that a given amount of water be used in such a way as to minimize the cost of running the thermal units. We will use Figure 2.12 in setting up this problem.



Where:

- j is interval
- r_j is inflow during j
- V_j is volume at end of j
- q_j is discharge during j
- S_j is spillage discharge during j
- P_H is hydro power
- P_S is steam power
- P_L is the load
- F is fuel cost of steam unit

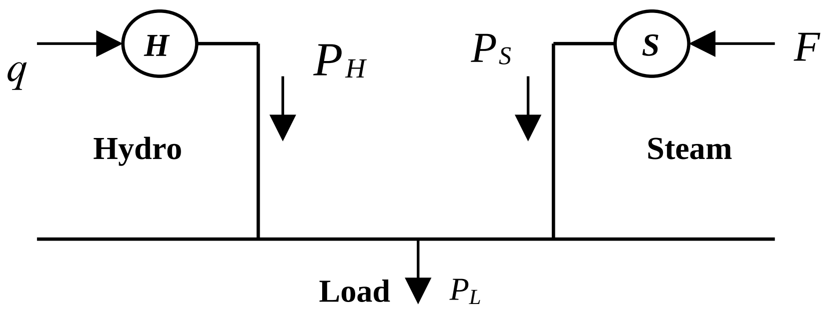


Figure 2.12 Hydrothermal systems with hydraulic constraints

The thermal system is presented by an equivalent unit P_S, and in this case is a single hydroelectric plant P_H. We assume that the hydro plant is not sufficient to supply all the load demands during the period and that there is a maximum total volume of water that may be discharged throughout the period of $T_{\max}$ hours. Also, we assume all spillages S_i are zero. With reference to section 7.4 of [18] taking into account a system loss, the mathematical scheduling problem may be set up as follows [18] :

Problem: $$Min\, F_T = \sum_{j=1}^{j_{\max}} n_j F_j \qquad (2.30)$$

Subject to: $$\sum_{j=1}^{j_{\max}} n_j q_j = q_{TOT}\,; \qquad \text{total water discharge}$$

$$P_{load\, j} + P_{Loss\, j} - P_{H\, j} - P_{S\, j} = 0\,; \qquad \text{load balance for } j = 1 \ldots j_{\max}$$

where

$$n_j = length\ of\ j^{th}\ \text{int}\,erval$$

$$\sum_{j=1}^{j_{\max}} n_j = T_{\max}$$

The loads are constant in each interval. Other constraints could be imposed, such as:

$$V_j\Big|_{j=0} = V_s \qquad \text{starting volume}$$

$$V_j\Big|_{j=j_{\max}} = V_E \qquad \text{ending volume}$$

$$q_{\min} \le q_j \le q_{\max} \qquad \text{flow limits for } j = 1 \ldots j_{\max}$$

$$q_j = Q_j \qquad \text{fixed discharge for a particular hour}$$

Assume constant head operation and assume a q versus P characteristic is available, as shown in equation (2.31). As the hydro generating unit, assume a fuel cost characteristic is made available as shown in equation (2.32).

$$q_j = q\left(P_{H\, j}\right) \qquad (2.31)$$

$$F_j = F\left(P_{S\, j}\right) \qquad (2.32)$$

Lagrange function becomes:

$$\mathscr{L} = \sum_{j=1}^{j_{\max}} \left[n_j F\left(P_{S\, j}\right) + \lambda_j \left(P_{load\, j} + P_{Loss\, j} - P_{H\, j} - P_{S\, j}\right)\right] + \gamma \left[\sum_{j=1}^{j_{\max}} n_j q_j \left(P_{H\, j}\right) - q_{TOT} \right] \qquad (2.33)$$

where;

λ_j Lagrange multiplier of balance load equation

γ Lagrange multiplier of total water discharge equation

$$n_j \frac{dF}{dP_{S\,j}} + \lambda_j \frac{\partial P_{LOSS\,j}}{\partial P_{S\,j}} = \lambda_j \tag{2.34}$$

$$\gamma\, n_j \frac{dq}{dP_{H\,j}} + \lambda_j \frac{\partial P_{LOSS\,j}}{\partial P_{H\,j}} = \lambda_j \tag{2.35}$$

$$P_{Loss\,j} = f\left(P_{S_j}\right) \tag{2.36}$$

Where,

$P_{Loss\,j}$ is the loss in power system.

With the coordination function and loss function as equation (2.34), (2.35) and (2.36), the $\lambda - \gamma$ iteration for hydro thermal scheduling algorithm is shown in figure 2.13 From the figure 2.13, the initial value for λ at any interval j and γ are determined. The λ_j, $P_{H\,j}$, $P_{S\,j}$ and $P_{Loss\,j}$ will be calculated from coordination and loss functions. The λ_j will be changed until the error from power balance equation is acceptable (ε_1). Next, the water release at the interval j will be calculated. The interval will be changed until the whole period is considered. The error from water release equation is the condition to stop scheduling. If the error is still higher than acceptable value (ε_2), the scheduling will be recalculated using a new γ .

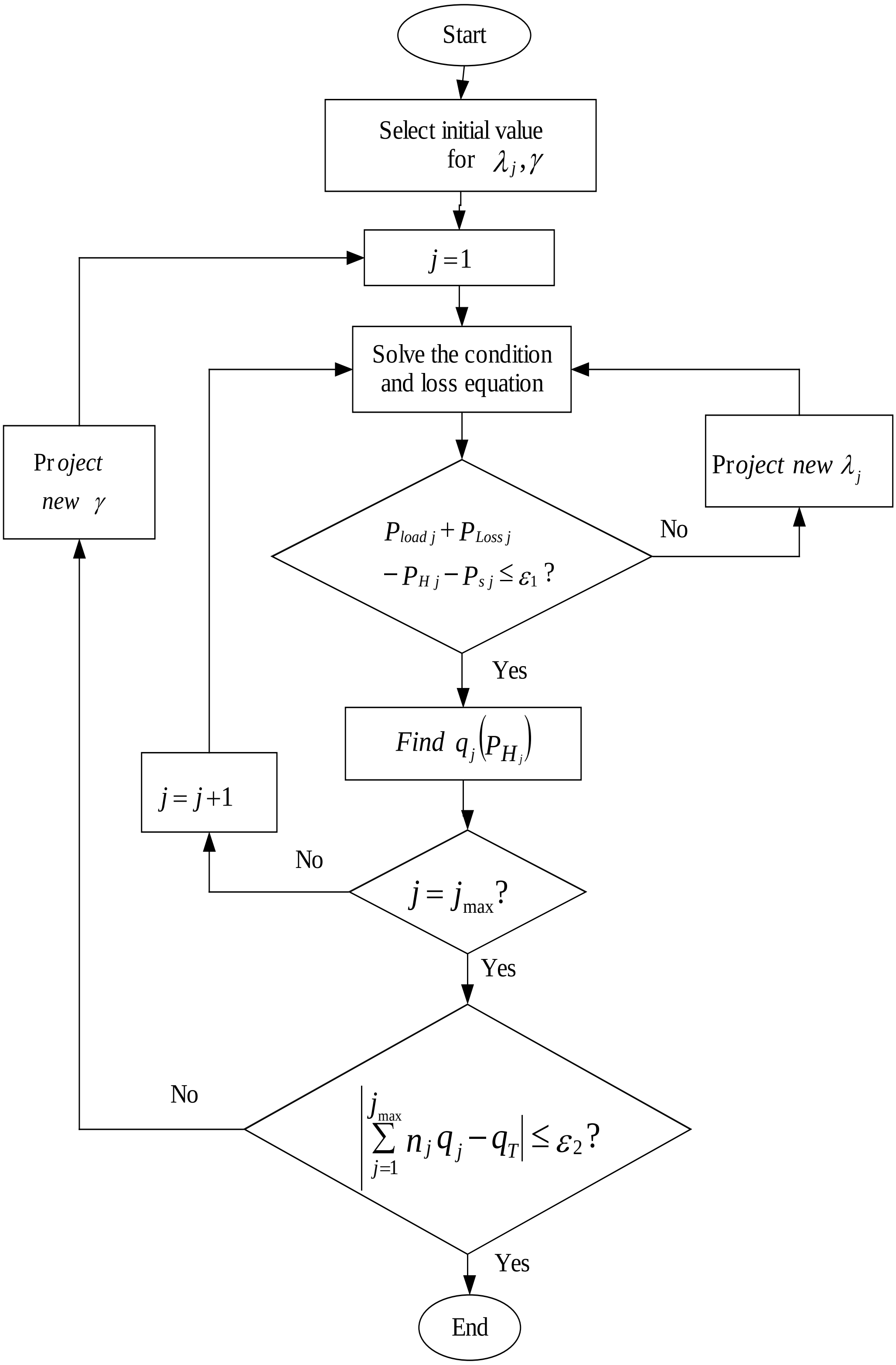


Figure 2.13 $\lambda - \gamma$ Iteration for Hydro Thermal Scheduling