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Model for Electricity Price in Hydroelectric Generating Stations under Deregulation

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Abstract – *This paper presents a mathematical model to determine the optimum electricity price in hydroelectric generating stations under deregulated electricity market. Under deregulation, a free market approach to buying and selling the electricity is established. In a deregulated power market, electricity producers generally follow a marginal cost based price fixing strategy. Accordingly, each utility firm follows their own pricing strategy in the market. Absence of a general model to determine the optimal electricity price at the generator end leads to non-standard pricing practices by different generators. The proposed model was formulated based on performance incentive and penalty considering peak/off-peak loads, plant load factor and availability of the plant. The developed model was applied to a typical hydroelectric utility in India to determine the electricity price. Results show that the percentage error in estimated value falls within the limits.*

Keywords – Deregulation, electricity price, power market, profit maximization.

1. INTRODUCTION

Competitive energy markets are instituted around the world and electric supply industries are restructured to compete in the new emerging markets [1]. Monopolized structure prevailed in old power systems has been broken and fully competitive and open power markets are emerging. This major shift, from the intensely regulated monopoly to a deregulated electricity market, result in better allocation of resources, thus supplying the end customer with a lower cost but high reliability energy supply [2]. Deregulation introduces competition among generation companies (GenCos) and improves the services for customers [3].

In developing countries, the power system deregulation and power markets are to establish fair competition among GenCos to encourage investments to power industry from various resources, such as foreign investments, local investments and IPP's, etc [4]. Under deregulated environment, private investors can take independent decisions according to their own assessments rather than those of the government regulated bodies [5]. Market participants, especially generation companies, who want to take profit from volatility or peak prices naturally begin to search for the ways to improve the returns by selling and buying energy, and then adapt their strategies to the changes of the prices [6].

In a country like India, electric power utilities are passing through a quick transition stage. Many states have already passed laws constituting separate generation, transmission and distribution companies. After the introduction of the Electricity Act 2003 along with Availability Based Tariff there is an increased realization that optimum pricing solutions leads to profits and sustainability. The Act is a move towards creating a market-based regime in the Indian power sector and consolidates the laws relating to generation, transmission, distribution, trading and use of electricity. It generally takes measures conducive to development of electricity industry, thereby promoting competition, protecting interests of consumers and supply of electricity to all areas [7]. The act envisages transforming the power sector from a system of monopoly providers at regulated rates to a system in which different companies compete to provide electricity [8].

There have been several attempts on the modeling of the electricity prices. The available literature has two main branches: statistical models and fundamental models. Statistical, or econometric, models follow the finance tradition of modeling directly the stochastic processes that represent prices. Fundamental, or structural, models build the price processes based on equilibrium models for the electricity market.

Due to non-storability of electricity the price formation as a continuous stochastic process is not supported but modeling the random characteristics of prices with stochastic processes is possible. Price volatility can be modelled either a deterministic one, a model with two regimes between which the price jumps, or with a stochastic one [9]. In the average power demand and generation capacity model, the electricity price switches randomly between two price regimes on the basis of the ratio between demand and capacity [10]. Hydro inflow, snow, and temperature conditions can be used to explain spot price formation [11]. Fundamental model for the electricity price dynamics incorporate the seasonality of prices, stochastic supply outages, and mean revision [12].

The generation business has been given a greater degree of freedom in fixing price structure, respecting a set of regulatory rules and possible revenue caps. The price of electricity has the key role of all activities in the power market and hence it is important to fix the price of

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electricity in a generating station more accurately and efficiently [13]. In a deregulated market, generators follow a marginal cost based pricing and electricity price varies with reliability of service, peak and off-peak period demand and each utility follows their own price fixing strategy. A standardized pricing approach will take care of volatility in demand and price. Hence, a more elaborate model becomes essential for electricity pricing under competitive markets.

This paper presents a mathematical model to determine the electricity price considering all operational constraints of the plant and economical variables that influence the price, for hydroelectric generating companies. This model can be used for calculating electricity price of different types of generators such as new and existing investors in power generation, independent power producers, investors in power exchange and utilities coming under regulatory authorities. It can be also used for estimating electricity price of storage type, pondage type and run-off- river type hydroelectric stations. The developed model is applied to a typical hydroelectric generating utility in India, for calculating the electricity price.

2. PROPOSED MODEL OF ELECTRICITY PRICING IN HYDROELECTRIC GENERATING STATIONS

The proposed mathematical model was designed in such a way that it can be applied for calculation of the electricity price in hydroelectric generating stations under deregulated market. In this model, generating company can collect ancillary service charges like reactive power control, voltage control and cess/surcharge etc in addition to the fixed cost and variable charges. The price structure was worked out based on peak load/off-peak load, plant load factor and availability of the plant. The main components of price structure are capital cost, fixed charges and variable charges.

Capital Cost

The capital cost varies with the size, location of the station and the type of equipment used. It also varies largely in tune with technology implemented. The generating company obtains the capital for financing their investment in the form of equity or debt or both. The components of the capital cost are actual expenditure for the project (C_1), cost of initial spares (C_2) and additional capitalization (C_3) subject to price variation. Additional capitalization includes cost of minor items, expenditure for price revision, deferred liabilities and works, expenditure on new work, modernization etc.C_4 is foreign exchange rate variation. Price variation includes the change in the cost due to foreign exchange rate, inflation or deflation. Capital cost (C) can be expressed as:

$$C = C_1 + C_2 + C_3 + C_4 \tag{1}$$

The equation for debt and equity are:

$$\text{Equity } E = (C) * Y / 100 \tag{2}$$

$$\text{Debt } L = C * (100 - Y) / 100 \tag{3}$$

Y is the percentage equity with the utility company.

Operating cost can be divided into two categories.

Fixed Charges

Fixed charges are proportional to the cost of installed capacity subject to auxiliary consumption. A cost escalation component was included to accommodate any variation in the initial project cost due to unexpected events. The components of the fixed charges are interest on loan capital, depreciation, and return on investment, operation and maintenance expense, interest on working capital, taxes and cost escalation component. Taxes and insurance are on land, building and on income. A generating company can choose these components as per the company policy. The mathematical equations of each component of fixed charges were derived separately as given below.

Interest in Loan Capital

The interest on loan is calculated either loan wise for new generating stations or considering previous years' loans for existing stations. Maximum opening loan is limited to debt in the capital cost. The mathematical equation for interest on loan capital incase of existing station is expressed as Y_1= (loan opening during the year + loan closing during the year)/2)* Interest rate. To calculate opening loan during the year, repayment up to the previous year is deducted.

$$IL_r = \begin{pmatrix} \left(t_r \times \left(Y_{11_r} - Y_{12_r}\right)\right) - \\ \left(\left(\left(t_r - 1\right) \times \left(\left(t_r - 1\right) + 1\right) / 2\right) \times Y_{13_r} / 2\right) \pm Y_{14_r} / 2 \pm Y_{15_r} / 2 \end{pmatrix} * r_{l_r}$$

$$W_r = \frac{\textit{Component of particular loan in the period}}{\textit{Toal loan amount}}$$

$$Y_1 = \sum_{r=1}^{L} IL_r \times W_r \tag{4}$$

Interest on loan for new power station is calculated on loan wise, then the equation is:

$$Y_1 = \sum_{r=1}^{L} IL_r \tag{5}$$

- Y_1 - interest on loan
- IL_r - interest of r^{th} loan
- Y_{11} - gross loan opening amount
- Y_{12} - cumulative repayment up to the previous year
- Y_{13} - principal repayment during the year depends on the number of installments
- Y_{14} - additional capitalization
- Y_{15} - foreign exchange rate variation
- Y_{54} - excess amount from the assessed equity over the equity from capital cost
- W - weighted average of the loan that depends on loan opening in particular period and total loan amount
- T - total number of installments
- t - number of loan installments that choose to calculate from the beginning loan. T varies from 1 to T.

Depreciation

Depreciation is the loss of value of an asset and is calculated asset wise. It depends on the size, type of equipment and its estimated life. Straight-line method was used to calculate depreciation.

Depreciation = (initial value – salvage value)* rate of depreciation.

$$Y_2 = \sum_{i=1}^{d} (bvi - svi) * r_{D_i} \tag{6}$$

Where, Y_2 – depreciation

d – number of assets

bv – initial value

sv – salvage value

r_D – rate of depreciation of the i^{th} asset

Advance against depreciation (Y_3) is an additional amount of depreciation. It is used as a cost component in the fixed charge when the loan repayment during the year is greater than depreciation [15,16]. This can help the cash flow in the utility and is applicable only to the generating stations, which comes under regulatory authority. In other cases, this is set to zero. Mathematical equation for AAD is:

$$Y_3 = \max\left(0, \min\left(Y_{11} / k, Y_{13}\right) - Y_2\right) \tag{7}$$

Where, k – loan repayment period.

Return on Investment / Return on Equity

A generating company can follow either return on investment or return on equity method according to the company's rule. Return on investment is a measure of a company's ability to use its assets to generate additional value for shareholders. It is calculated as net profit after tax divided by net assets and expressed as a percentage [14].

$$Y_4 = C * (Y_{41} - T) / Y_{42} \tag{8}$$

where, Y_4 – return on investment

Y_{41} – earnings before interest and tax

T – corporate tax

Y_{42} – net assets

Return on equity is applicable only to generating stations that come under regulatory authority. Any change in foreign exchange rate variation and additional capitalization affects equity. Equity is limited to specified percentage of capital cost [15], [16]. If the assessed equity of the generating company is greater than the specified percentage of the capital cost, assessed equity is made equal to the equity specified by regulatory authority.

$$Y_5 = \min\left(Y_{52}, Y_{53}\right) * r_e \tag{9}$$

where, Y_5 – return on equity

Y_{52} – assessed equity of the generating company

Y_{53} – equity derived from the capital cost

r_e – rate of return on equity

$$Y_{54} = \max\left(\left(Y_{52} - Y_{53}\right), 0\right) \tag{10}$$

Y_{54} is the difference between assessed equity of the company and equity derived from capital cost.

Instead of return on equity or return on investment, the company can use Internal Rate Return (IRR). IRR is the discounted rate at which the project's net present value is zero. Under IRR rule, the project will be accepted when IRR is higher than the cost of the capital. This is an indication of sustainability.

Operation and Maintenance Expense

Operation and maintenance cost depends on the capacity of the plant. It includes expenditure on spares and repairs, administration, labor charges and other miscellaneous expenses for the up keep of the building and machinery. Operation and maintenance expense can be calculated using average method or comparison method.

In average method, previous years O and M expense data are required to calculate the base value of O and M expense and can be indexed to calculate O and M for subsequent years. Index value depends on whole sale price index and consumer price index. Hence O and M expense is:

$$Y_6 = \sum_{yi=yst}^{yed} \left(\frac{\left(OM_{yi} - OMabn_{yi}\right)}{y} \right) * (1+if)^{(n_4 - n_3)} \tag{11}$$

where, OM_{yi} – operation and maintenance expense

OMabn – abnormal operation and maintenance for y_i^{th} year

y – number of years for which O and M expense data is taken to calculate base year O and M expense

n_4 – year for which price is calculate

n_3 – base year

yst and yed are starting and ending year for the calculation of base year O and M expense

if – inflation/deflation rate that depends on whole sale price index and consumer price index

Interest on Working capital

Working capital is usually used for the purchase of raw materials, components and spares, payment of wages and salaries, the day-to-day expenses and overhead costs such as power and office expenses, etc. The interest on working capital is determined on normative basis. The mathematical equations for calculating the interest on working capital is derived as:

$$Y_7 = (Y_6 * t_1 + Y_{71}(1 + esf)^{(y2 - cod}) * r_w \tag{12}$$

where, Y_6 – O and M expense

Y_{71} – cost of maintenance spares

y_2 – year for which working capital is to be found

cod – date of commercial operation

t_1,– time period that may be 1week to 12months and it is decided by the availability of the items and location of the plant and decision of the utility.

r_w – interest on working capital

esf – escalation factor and its depends on increase in price due to availability and inflation

The mathematical equation for calculating fixed charge/year is:

$$FC = \sum_{r=1}^{L} IL_r \times W_r + \sum_{i=1}^{d} (bvi - svi) \times r_{D_i} + \max\left(0, \min\left(Y_{11}/k, Y_{13}\right) - Y_2\right) + C \times (Y_{41} - T)/Y_{42} + \min\left(Y_{52,} Y_{53}\right) \times r_e + \sum_{yi=yst}^{yed} \left(\frac{\left(OM_{yi} - OMabn_{yi}\right)}{y} \right) \times (1+if)^{(n4-n3)} + (Y_6 \times t_1 + Y_{71}(1+esf)^{(y2-cod)}) \times r_w + Y_8 + Y_9 \quad (13)$$

Y_8 is the cost escalation factor and it is the increase in cost due to unexpected events and Y_9 is the tax. The above equation is a non-linear equation.

Energy Charges

The energy charges are based on ex-bus energy delivered. The ex-bus energy depends on hydraulic head (h) reservoir volume of water (V), discharge of the water (Q), plant load factor, time of operation, auxiliary consumption of the station, transformation and transmission losses and design energy of the station, overall efficiency of the generator. The run of river plant utilizes the water as when available and hence there will be large variation in discharge. If there is any upstream plant, water travel time delay from the upstream plant to the operating the plant must be also considered. In hydroelectric generating stations water is the source of energy. The rate of generation cost/unit can be set between a minimum and maximum price depending on the discharge, head of the water, volume of water and number of machines. The price of electricity from the hydroelectric generating station offered in the competitive market should fall within this range. The energy generated by utility can be found using the following formula:

$$E_d = E_g - aux - TL \quad (14)$$

$$RG/unit = Running\ charges/E_g \quad (15)$$

$$EC = RG/unit * E_d \quad (16)$$

where, E_g – maximum energy available generated
Ed – energy delivered
RG/unit – rate of generation/unit
Aux – auxiliary consumption of the station
TL – transmission and transformation losses
EC – energy charges

Scheduling of the machine is done so that most efficient machine can run first without violating the constraints and thus reduce the rate of generation cost/unit. The constraints are:

1.Generation constraints:

$$P_{G(i)min} \le P_{G(i)} \le P_{G(i)max} \quad (17)$$

$$P_G > Pd \quad (18)$$

Where $P_{G(i)min}$, $P_{G(i)max}$, are minimum and maximum generation
P_G – total generation in the station
Pd – load demand

2. Hydraulic network constraints

The hydraulic operational constraints comprise the water balance (continuity) equation for each hydro units as well as the bounds on reservoir storage and release targets. These constraints include:

(i) Physical limitations on reservoir storage volumes and discharge rates:

$$V_{(i)\max} \le V_{(i)} \le V_{(i)\max} \quad (19)$$

$$Q_{(i)\min} \le Q_{(i)} \le Q_{(i)\max} \quad (20)$$

Where $Q_{(i)\ min,}$ $Q_{(i)\ max}$ are minimum and maximum discharge and $V_{(i)\ min}$, $V_{(i)\ max}$ is the maximum volume of water for the i^{th} generator.

(ii) The desired volume of water to be discharged by each reservoir over the scheduling period.

$$V_{(i,t)}|^{t=0} = V_i^{\ start}$$
$$V_{(i,t)}|^{t=T} = V_i^{\ end} \quad (21)$$

Where, V_i^{start} – initial volume of water,
V_i^{end} – final volume of water at the time of generation.

Operational charges (OC)

This includes the charges for running the plant and that for breakdown maintenance of the equipment.

Other Service Charges (OSC)

OSC includes reactive power control, voltage and frequency control and levy or duty paid by the utilities to the authority. Figure 1 shows the model for fixing electricity price in hydroelectric station.

EP = FC/MW + EC + OC+ OSC + Cess/service tax implemented by the government.

$$EP = \begin{bmatrix} \sum_{r=1}^{L} IL_r \times W_r \\ + \sum_{i=1}^{d} (bvi - svi) * r_{D_i} + \max\left(0, \min(Y_{11}/k, Y_{13}) - Y_2\right) \\ + C*(Y_{41} - T)/Y_{42} + \min\left(Y_{52,} Y_{53}\right) * r_e \\ + \sum_{yi=yst}^{yed} \left(\frac{\left(OM_{yi} - OMabn_{yi}\right)}{y} \right) * (1+if)^{(n4-n3)} \\ + (Y_6 * t_1 + Y_{71}(1+esf)^{(y2-cod)}) * r_w + Y_8 + Y_9 \end{bmatrix} * \left(\frac{1*MF}{12*N*IC} \right) + EC + OC + OSC + cess / servicetax \quad (22)$$

where N – time of operation
IC – installed capacity of the station
MF – a factor for considering outage/maintenance of the generating units (MF = 1, if all generating units are ON and can be find out using the expression MF = no of units are ON/total no of units in the station)

The above equation is a non-linear one and it contains more number of variables. The objective function is to minimize electricity price. The constraints are:

1. $P_{G(i)min} \le P_{G(i)} \le P_{G(i)max}$

2. $P_G > P_d$
3. $V_{(i)\,max} \leq V_{(i)} \leq V_{(i)\,max}$
4. $Q_{(i)\,min} \leq Q_{(i)} \leq Q_{(i)\,max}$
5. $V_{(i,t)}\,|^{t=0} = V_i^{\,start}$
   $V_{(i,t)}\,|^{t=T} = V_i^{\,end}$

The variables considered for optimization are Y, rl, rd, Y_{11}, k, rw, index factor (if), r_e, r_i, esf and discharge of water from the generator. It is multivariable, dynamic, profit maximization, performance based model. The model will take care of outage/breakdown maintenance of the generating units. Using this model the utility can find their bare minimum electricity price.

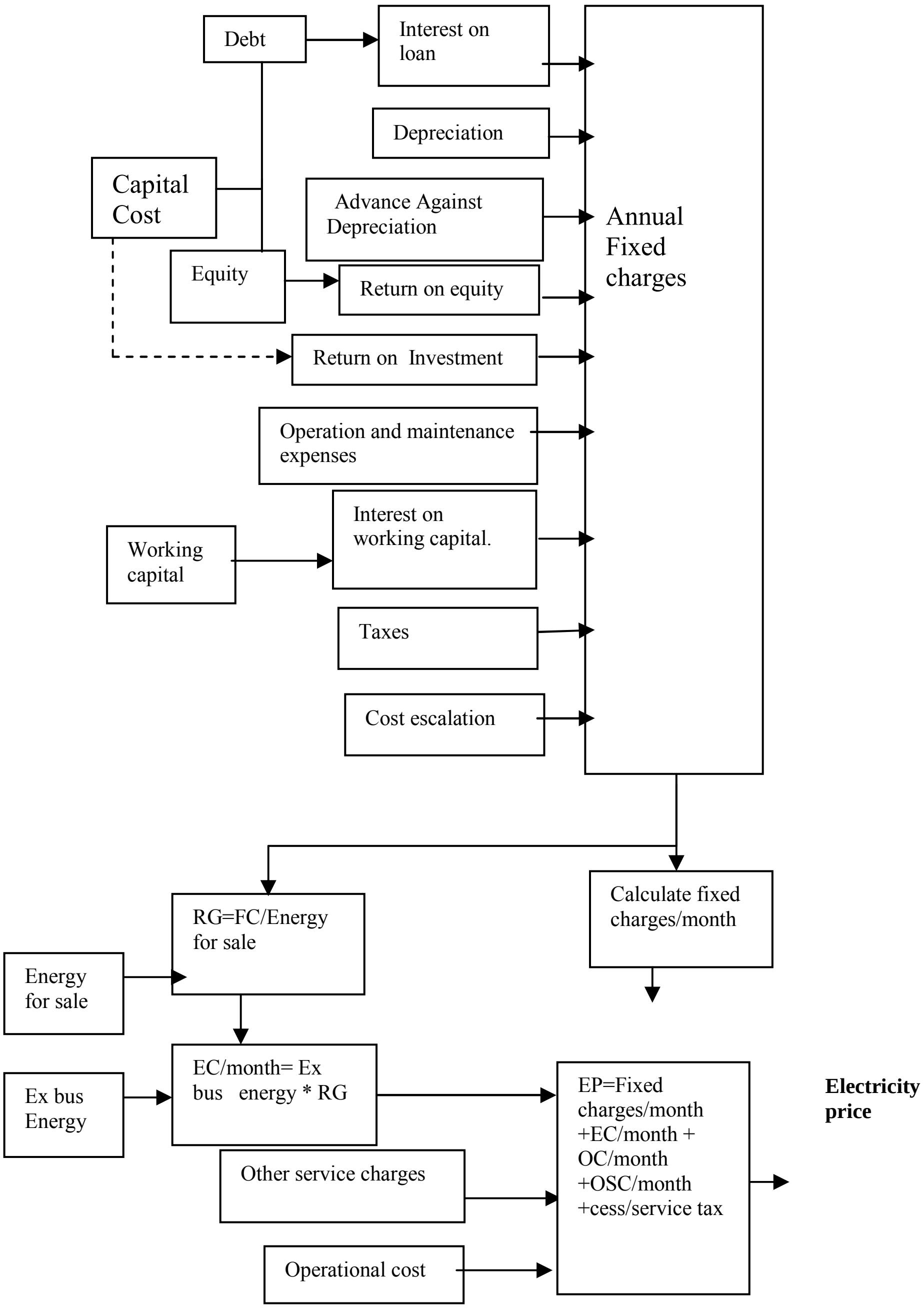

Fig. 1. Model for fixing the electricity price

Incentives/Penalty

The generating company can achieve incentives for maintaining reliable and quality power. Incentive is based on the declared capacity in MW corresponding to the generation and the incentive rate is in paise/kWh. A penalty clause also can be added for not maintaining quality and reliability of power and for violating the constraints.

3. OPTIMIZATION OF ELECTRICITY PRICE

Genetic algorithm was used to optimize the electricity price. The problem formulation of GA for electricity price can be done as follows:

String representation:

The parameters of the problem are represented using series of binary, decimal or floating-point numbers, so called string. The variables are considered as genes. The variables are z, Y, rl, r_{Di}, re, ri, esf, k, y, rw, Q_i. Decimal coding was used in this work.

Generation of initial string population

Initial strings in the population were generated randomly. Each gene of string was encoded with a value satisfying the upper and lower boundaries of variable.

Evaluation of chromosomes

It consists of the following steps.

1. Calculation of y1, y2, y3, y4, y5, y6, y7
2. Calculation of fixed charge
3. Calculation of rate of energy charge/unit
4. Calculation of generation outputs and continued computation for each plant from upstream to downstream and for hour 1 to 24
5. Calculate energy charge
6. Calculate operational charges
7. Add other service charges
8. Calculation of the fitness function – the fitness function adopted is the electricity price.

Fitness scaling

The genotype fitness was scaled by a nonlinear transformation in order to emphasize the “best” chromosomes and speed up the convergence of the evolutionary process. Fitness was normalized in to the range between 0 and 1.

Selection of chromosomes

The fitness of each chromosome was calculated and was stored in descending order. Roulette wheel parent selection techniques was used to select the best parents for cross over and mutation according to their fitness.

Eitism

The best solution of every generation was copied to the next so that possibility of its destruction through a genetic operator is eliminated.

String operations

When cross over and mutation were performed, strings that satisfy constraints were generated. The cross over used in this work was a simple one point cross over.

GA has a number of parameters such as selection method, population size, crossover method, crossover rate and mutation rate. Cross over rate was 0.95 and mutation rate was 0.05. The genetic iterations proceeded to search the optimal chromosome which has the lowest electricity price.

Implementation of GA based electricity price

The genetic algorithm was implemented in software written in C language and executed on Pentium PC. This software was tested on test system. The result was also compared with that of calculated value. Figure 2 shows the flow chart for electricity price using GA.

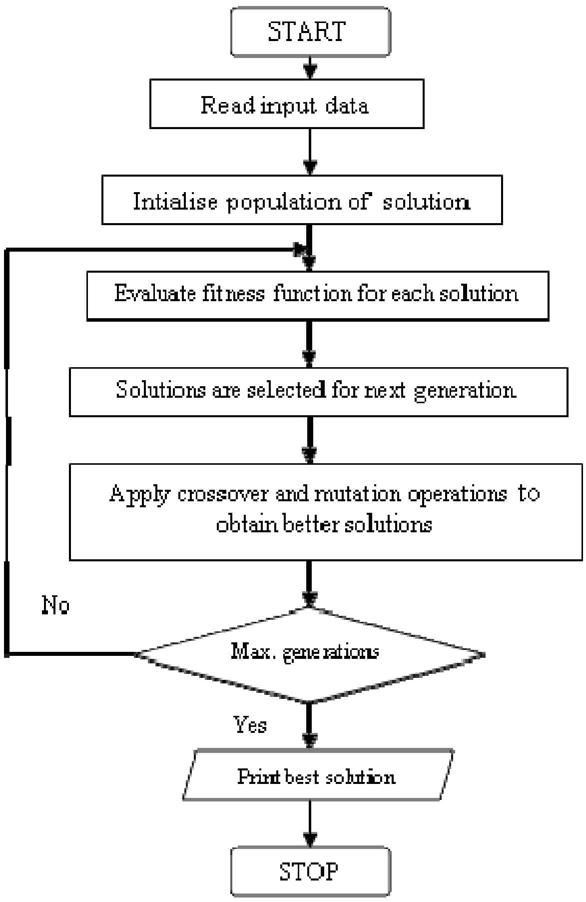

Fig.2. Flow chart for electricity price using GA

4. CASE STUDY

A case study for calculating the electricity price was done for a typical storage type hydroelectric utility in India. It has an installed capacity of 780 MW having six machines of each having capacity 130 MW, PLF is 35.9%, average net effective head 2147.88 M, maximum generation is 680 MW and minimum generation is 30 MW. Full reservoir level is 732.43 M, full load discharge of one machine 24.5m^3/sec., maximum volume of the water in the reservoir is 1459.7 MCM and dead storage is 536.86 MCM. It is calculated that water required for generation of one million unit is 0.6796 MCM. Auxiliary consumption of the station is taken as 1% and transmission and transformation losses is 2.5%.

The machines in storage type can be taken for maintenance during the period of rainy season one at a time. For the rest of the year all generators are operated. The discharge of water from each machine was maintained as constant during particular period. The results of the case study are shown in figures. The fixed charge depends on the installed capacity of the machines and rate of generation/unit depends on fixed charge, the volume of water and head of the water. In the absence of outages/shut down, monthly demand charges remain constant. Rate of generation/unit depends on the availability of the water. Optimization of this fixed charge is done by using a software program developed for this purpose. The variables selected for optimization are Y, r_l, k, Y_{11}, r_{Di}, r_e, y, r_w, if, esf. Each variable has lower and upper limits. By considering volume of water, head and discharge of water, each utility can set their minimum and maximum rate of generation /unit.

Figure 3 shows monthly variations in volume of water. Figure 4 shows the rate of generation/unit for the corresponding volume of water. The results shows that, rate of generation/unit is inversely proportional to volume of the water. Figure 5 shows variations of monthly rate of generation/unit, and from June to November the availability of water is high and rate of generation/unit is less in this period. The utility can reserve the excess available water in the monsoon season after meeting the demand in market for use during the summer when availability of water is less. Thus, they can reduce the price of electricity when the water is less. There is flexibility to add operational cost and other service charges as a cost component. This enables a more rational work out of electricity price in a market driven system. The availability of plant depends on the time of operation. If the availability is high the utility can achieve incentives. As availability of the plant is high, plant use factor is also high. The plant load factor depends upon time of operation. Hence, electricity price mainly depends on the plant load factor, plant capacity factor and plant use factor. The financial policy of the generating station mainly depends on these three factors.

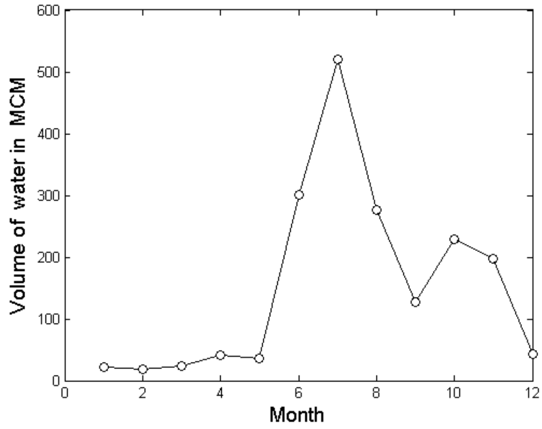

Fig. 3. Variation of volume of water/month

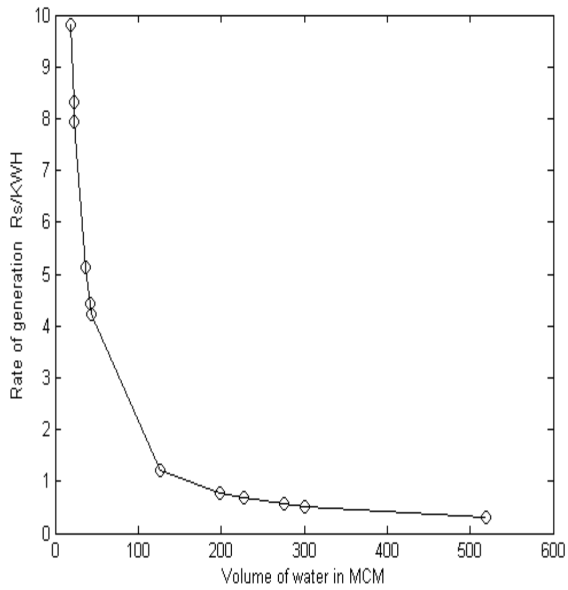

Fig. 4. Variation of rate of generation/unit with volume of water

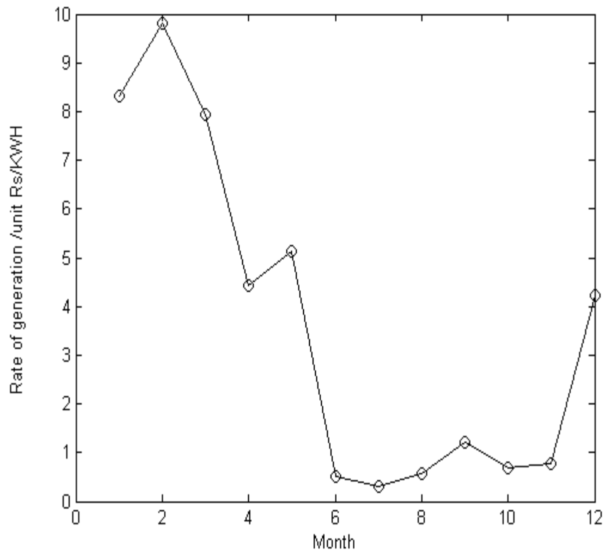

Fig. 5. Variation of rate of generation/ unit/month

5. CONCLUSION

The model for calculating the electricity price is a non-linear equation. In this model, more parameters were chosen as variables and solved by numerical methods. The model parameters were selected suitably for fixing the electricity price in generating companies. Optimization of the model will yield an optimum price for electricity. Prices were generally worked out for the full capacity of the generator. In case of outages in one or more generators in a station, this model enables better calculation of demand charge and rate of generation/unit by taking out the capacity of the outage machines, and it takes care of variations inflow which in turn is caused by rainfall variation. The model can be used for calculating electricity price of different types of generators such as new and existing investors in power generation, independent power producers, investors in power exchange and utilities coming under regulatory authorities. This provides for setting the minimum and maximum limit of the rate of energy charge as required by the deregulated market situations. It enables decision on production or purchase in case of very high rate of energy charges.

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