SHORT-TERM SCHEDULING OF A HYDRO-THERMAL SYSTEM USING LINEAR PROGRAMMING TECHNIQUE

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The paper discusses the short term scheduling of Hydrothermal for Tanzania Electricity Supply Company (TANESCO) Power System. The problem is to determine on hourly interval the Hydro and Thermal generation. The scheduling keeps balance between production and consumption in a reliable and economical way during the study period. Linear programming (LP) mathematical model using MATLAB has been developed. The constraints are hydrological balance, thermal power plants limitations and load requirements. The result from LP solution gave low operation cost. Generation was mainly from hydro and all reservoirs elevation was high at the end of planning period.

Keywords: *Generation, hydrothermal, optimization, unit commitment, short-term.*

INTRODUCTION

In TANESCO grid (interconnected) power system, there are six major hydro power stations. Nyumba ya Mungu, Hale and New Pangani Falls power stations are in Pangani River while Mtera and Kidatu power stations are in Great Ruaha River. Kihansi power station is in Kihansi River. In addition to that, there are several thermal power plants, a gas turbine power station and Diesel power station at Dar es Salaam. There are also Diesel power stations at Mwanza, Musoma, Tabora, Dodoma and Mbeya. Total installed capacity for grid hydro power plants is 560 MW and for thermal power plants is 202 MW, while maximum demand is around 440 MW. Most of the commercially available software for hydrothermal scheduling are developed for thermal dominated Power systems or at least for thermal power generation equals to the total demand (e.g. WASP1, SYRAP2). This is not the case for Tanzania system, which depends much on Hydro generation. Thus, in Tanzania the dry years will not only raise the power price but also may cause power-rationing problems, as thermal power plants may not meet the total demand [Mwakabuta and Kyaruzi, 2001].

As shown in Figure 1, there are 6 major hydro power stations. Nyumba ya Mungu, Hale and New Pangani Falls power stations in Pangani River while Mtera and Kidatu power stations in Great Ruaha River. Also Kihansi power station in Kihansi River. The technical data of all these hydro power station are summarized in the Table 1.

The TANESCO Grid Thermal power system

There are several thermal generators, four gas turbine generators at Ubungo (Dar es Salaam) with installed capacities of 2 x 37.5 MW, 2 x 18.5 MW and Diesel generators at Ubungo (29 MW), other Diesel generator stations are at Mwanza (12 MW), Musoma (5.12 MW), Tabora (9 MW), Dodoma (6.5 MW) and Mbeya (13.7 MW). (IPTL capacity is not included).

The thermal generators are assumed to be readily available at any time required, although they have to be used so as to minimize the overall

1 WASP is the power system planning software developed by the International Atomic Energy Agency

2 Short-term hydrothermal planning software [7]

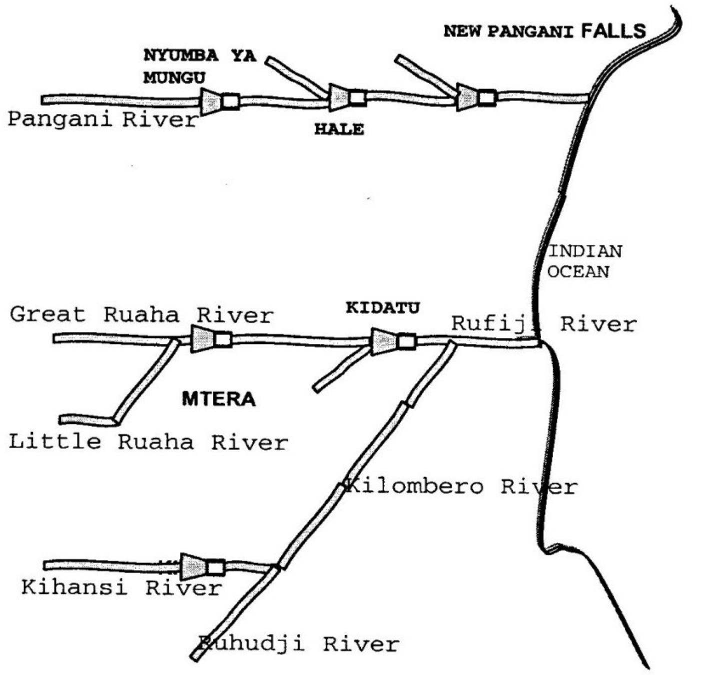

Figure. 1: Hydropower representation of TANESCO Power System

cost of the power system [Mwakabuta and Kyaruzi, 2001].

Operating costs of hydro generating plants are very low compared to thermal generating plants. In order to optimise the system, hydro power stations should operate at their maximum while the operation of thermal power plants must be minimized so as to reduce the usage of fuel. At the same time the overall generation should meet the required demand and water in reservoirs must be sufficiently conserved to serve the load for the entire year. This means that the short term planning schedule must follow the long term planning.

There are many ways of solving the hydro-thermal scheduling problem, the problem can be solved by: linear programming, priority-list Methods, dynamic programming, Lagrange relation, integer and mixed-integer programming, branch-and-bound, dynamic and linear programming, separable programming, network flow programming, expert systems/artificial neural networks, risk analysis, simulated annealing, augmented Lagrangian, decision analysis, Calculus, e.t.c [Bonaert, et al, 1972; Tang and Luh, 1995;. Nanda and Bijwe, 1981; Soares and Ohishi, 1995]. In this paper linear programming technique has been used.

Production as a function of discharge

The relationship between generation/production and water discharge is non-linear, it is also more complicated for the station having more than one unit, whereby; there are several local maximal points. Piece wise linear approximation model is suitable for this purpose as in linear programming; the solution points are always in corners, i.e. the solution will coincide with zero (no generation point), local maximal and maximum generation points. In other words, the solution from linear programming takes care for the hydro power plants not to operate in forbidden zones; the corners are the desired solution in Hydro generation. Depending on the number of maximal efficient points, example from Fig. 2 there are four segments, so in this case there are four-generation zones, which will be used in linear programming formulation [Nilson, 1997].

FORMULATION OF THE PROBLEM

The hydrothermal scheduling problem can be formulated as follows;

Table 1. TANESCO Hydro power stations data

	MTERA	KIDATU	KIHANSI	NYUMBA YA MUNGU	HALE	NEW PANGANI FALLS
Year of completion	1988	1980	2000	1969	1964	1995
Type of power station	Regulated	Regulated	Run of the river	Regulated	Run of the river	Run of the river
Gross head [m]	100	175	850	27.43	72	170
Mean annual inflow [m^3/s]	100	54	15	17	5	0
Design flow [m^3/s]	96	144	24	42.6	41	45
Number of units	2	4	3	2	2	2
Type of turbine	Francis	Francis	Pelton	Francis	Francis	Francis
Installed capacity [MW]	80	204	180	8	22	68
Average annual production [GWh]	419	1,150	474	47	125	407
Height of dam [m]	50	40	21	41	7.2	8.2
Length of dam crest [m]	260	350	200	400	340.5	310
Volume content of dam [10^6 m^3]	3,700	167	1.2	1,300	1.81	0.8
Active storage of the reservoir [10^6 m^3]	3,200	125	1	1128	1.1	0.55
Maximum discharge capacity of spillways [m^3/s]	4,000	6,000	280	6,000	818	1200

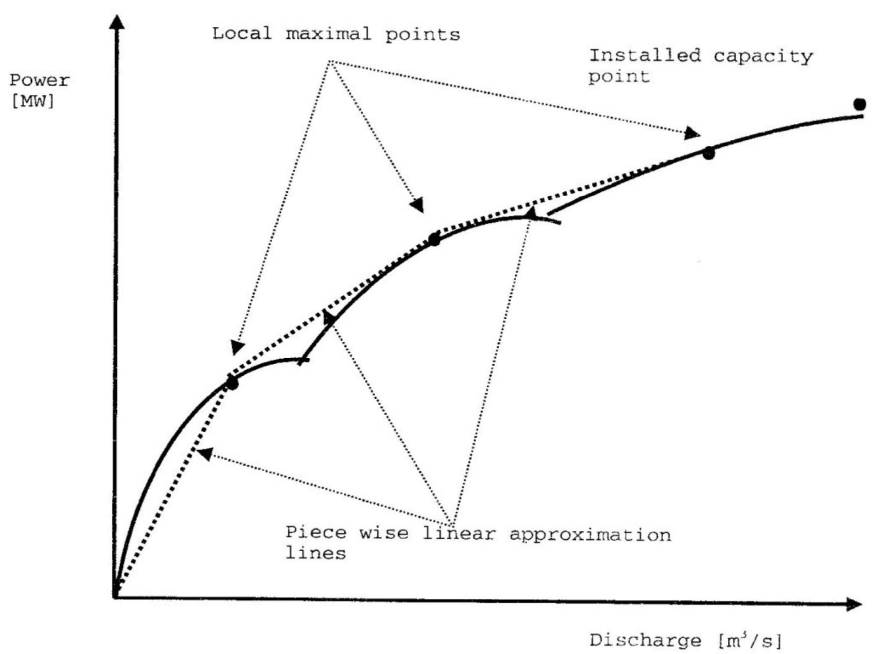

Figure 2: Linearlization of power generation as a function discharge

Maximize

Value of stored water in the reservoirs, while minimizing the operation costs for thermal power plants

Subjected to

- Hydrological balances for Mtera, Kidatu, Nyumba ya Mungu, Hale, New Pangani Falls and Kihansi power stations.
- Thermal power plants constraints.
- Contracted load at each period.

Limits

In reservoir contents, stations discharges, spillage and thermal generation capacities.

$$\text{i.e.}\quad \begin{aligned} &Min \quad f^T x \\ &Subjected \quad to \quad Ax = b \\ &Limits \quad l \leq x \leq u \end{aligned} \qquad (1)$$

where f^T is the transpose of matrix f

f is the column matrix containing the objective function, function to be minimized (negative for maximization).

x is the column matrix containing variables for the optimization problem.

A is the matrix containing left hand side of the constraints equations (variables).

b is the column matrix containing the right hand side of constraints equations (constants).

l is the column matrix containing the lower limits of all variables

u is the column matrix containing the upper limits of all variables

The variables and parameters

Indices for hydropower stations: Kihansi *1*, Mtera *2*, Kidatu *3*, Nyumba ya Mungu *4*, Hale *5*, New Pangani Falls *6*.

Indices for Thermal power stations: Gas Turbine-1&2 *1*, Gas Turbine-3&4 *2*, Ubungo Diesel *3*, Mwanza Diesel *4*, Musoma Diesel *5*, Tabora Diesel *6*, Dodoma Diesel *7*, Mbeya Diesel *8*

The optimization variables in this problem are;

$u_{ij}(k)$ = discharge in station i, linear segment j, sub-period k, $i = 1,..,6, j = 1,..,4, \ k = 1,..,24$,

$s_{ij}(k)$ = spillage in station i, linear segment j sub-period k, $i = 1,..,6, \ j = 1,..,4, \ k = 1,.., 24$,

$x_i(k)$ = contents of reservoir i at the beginning of sub-period k, $i = 1,..,6, \ k = 2,.., 25$,

$G_i(k)$ = Generation in thermal unit i, sub-period k

The following parameters are from the system data:

$\overline{u}_{ij}$ = maximum discharge in power plant i, linear segment j

$\overline{x}_{ij}$ = maximum contents of the reservoir i, linear segment j

w_i = local inflow to power station i

$D(k)$ = contracted load for sub-period k

$x_i(1)$ = start contents of reservoir i

ct_i = operational cost for thermal unit i

$\overline{G}_i$ = maximum generation in thermal unit i,

The following parameters can be calculated from data given.

μ_{ij} = marginal production equivalent for station i, linear segment j

μ_i = average marginal production equivalent for station i

Objective Function

Maximize

$$c \times \left[\sum_{i=1}^{6} \sum_{j=1}^{4} \sum_{k=1}^{24} \mu_{ij} u_{ij}(k) + (\mu_1 x_1(25) + (\mu_2 + \mu_3) x_2(25) + (\mu_3 x_3(25) + (\mu_4 + \mu_5 + \mu_6) x_4(25) + (\mu_5 + \mu_6) x_5(25) + (\mu_6 x_6(25) \right] - c_{ti} \times \left[\sum_{k=1}^{24} \sum_{i=1}^{8} G_i(k) \right] \qquad (2)$$

Constraints

For all k, k = 1... 24

Hydrological balance for Kihansi

$$x_1(k+1) = x_1(k) - \sum_{j=1}^{4} u_{1j}(k) - \sum_{j=1}^{4} s_{1j}(k) + w_1(k) \qquad (3)$$

Hydrological balance for Mtera

$$x_2(k+1) = x_2(k) - \sum_{j=1}^{4} u_{2j}(k) - \sum_{j=1}^{4} s_{2j}(k) + w_2(k) \qquad (4)$$

Hydrological balance for Kidatu

$$x_3(k+1)=x_3(k)+\sum_{j=1}^{4} uy_{2j}(k)+\sum_{j=1}^{4} sy_{2j}(k)-\sum_{j=1}^{4} u_{3j}(k)-\sum_{j=1}^{4} s_{3j}(k)+w_3(k) \qquad (5)$$

$uy_{2j}(k)$ and $sy_{2j}(k)$ are the discharge and spillage from Mtera. The spillage and discharge from Mtera takes 18 hours to reach Kidatu.

Hydrological balance for Nyumba ya Mungu

$$x_4(k+1)=x_4(k)-\sum_{j=1}^{4} u_{4j}(k)-\sum_{j=1}^{4} s_{4j}(k)+w_4(k) \qquad (6)$$

Hydrological balance for Hale

$$x_5(k+1)=x_5(k)+\sum_{j=1}^{4} uy_{4j}(k)+\sum_{j=1}^{4} sy_{4j}(k)-\sum_{j=1}^{4} u_{5j}(k)-\sum_{j=1}^{4} s_{5j}(k)+w_5(k) \qquad (7)$$

$uy_{4j}(k)$ and $sy_{4j}(k)$ are the discharge and spillage from Nyumba ya Mungu. The spillage and discharge from Nyumba ya Mungu take about 6 days to reach Hale, for this case the estimated values for discharges and spillage from Nyumba ya Mungu to Hale has been used based on experience.

Hydrological balance for New Pangani Falls

$$x_6(k+1)=x_6(k)+\sum_{j=1}^{4} u_{5j}(k-1)+\sum_{j=1}^{4} s_{5j}(k-1)-\sum_{j=1}^{4} u_{6j}(k)-\sum_{j=1}^{4} s_{6j}(k)+w_6(k) \qquad (8)$$

The spillage and discharge from Hale takes 1 hour to reach New Pangani Falls.

Power balance equation:

$$\sum_{i=1}^{6}\sum_{j=1}^{4} \mu_{ij} u_{ij}(k)+\sum_{i=1}^{8} G_i(k)=D(k) \qquad (9)$$

Limits

Hydrological limits

Limits on discharge

$$0 \le u_{ij}(k) \le \bar{u}_{ij} \qquad (10)$$

Limits on spillage

$$0 \le s_{ij}(k) \qquad (11)$$

Limits on reservoir contents

$$\underline{x}_i \le x_i(k) \le \bar{x}_i \qquad (12)$$

Limits in thermal generation

$$0 \le G_i(k) \le \overline{G}_i \qquad (13)$$

[IEE Working Group Report, 1981; Nilson, 1997 and Wood and Wollenberg, 1996]

RESULTS AND DISCUSSIONS

In each hydro power station there are at least two generating units, in this case, four segments piecewise linear model has been applied to solve hydrothermal optimization problem. In order to test the TANESCO power system five cases have been used, i.e. heavy load, medium load, light load, loads at highest reservoir levels and loads at lowest reservoir levels. The data under test are from generation and forecasting data of TANESCO from 1998 to 2001.

In Table 2, the result of generation schedule for 8th November 1999 is presented. The results obtained shows that; the model developed is appropriate for the test system. Because, generally, results give the schedules which are optimized, the usage of thermal power plants is minimized and water in the reservoirs is highly conserved so that it might be used after the planning schedule.

Linear programming solution has been used to find the optimal schedule for the generation of electricity for the year 2000. The aim of this solution was to compare the reservoir elevation levels at the end of the planning period, for this particular case period of one year is considered. The year period has been divided into 52 sub-periods, each sub-period represent one week. The actual reservoir levels of each month are shown in table 3.

The simulation results in Table 4 using linear programming provides a schedule with higher reservoir elevation levels compared to the actual operation of the test power system. Although the usage of the thermal power generators was minimized by the LP solution; the higher reservoir elevation levels suggests that, if the LP solution would have been used in the operation of the test system for the year 2000, then water in the reservoir would have been conserved more, which could have been used in the successive years.

CONCLUSION

The short term of Hydrothermal planning for TANESCO Power System has been presented. The problem was to determine the Hydro and Thermal generation for 24 hours in the hourly intervals. The aim of the planning was to keep the balance between the production and consumption in a reliable and economical way during the study period. Mathematical model for all generators has been developed and applied in a linear programming problem.

Linear formulation has made it possible to use commercially available optimization programs, such as public domain routine for MATLAB. This optimization problem is subjected to hydrological balance for all hydro power stations (since hydro energy is limited depending on inflow and reservoirs contents capacities). In addition, the constraints in thermal power stations and the load requirements have been taken into account. The result from the linear programming solution has provided an optimal and detailed schedule on how to operate each power station during the study period.

The results from the linear programming solution shows that the computation time was reasonable, about 10 – 16 minutes; this is due to the consideration of detailed piece wise linear model in this work, since the more detailed model is, the more computation time will be required. The results from the LP solution for the

Table 2: Generation Schedule for 8th Nov. 1999

	Mtera	Kidatu	Nyumba ya Mungu	Hale	New Pangani Falls	Thermal generation
Actual generation [MW]	1703	3068	147.80	259.80	961	608.78
Generation from LP solution [MW]	831	4566	104	227	1026	18
Water levels before and after actual generation [masl[3]]	695.67 695.65	447.21 447.21	687.76 687.75	N/A	N/A	N/A
Water levels before and after planning period [masl]	695.67 695.66	447.21 445.61	687.76 687.76	N/A	N/A	N/A

Table 3: Actual reservoir elevation levels

	Reservoir elevation levels (actual generation)[masl]			
	Kihansi	Mtera	Kidatu	Nyumba ya Mungu
Starting values	1145.71	698.81	445.52	687.01
End of Month				
January	1145.11	694.38	447.73	686.83
February	1145.80	693.96	449.00	686.3
March	1143.90	693.96	448.72	685.81
April	1146.39	693.84	446.61	685.56
May	1144.48	693.58	448.74	685.63
June	1144.74	693.41	448.24	685.53
July	1145.64	693.02	449.08	685.26
August	1142.33	692.53	448.79	685.05
September	1141.93	691.35	444.90	684.74
October	1142.41	691.06	445.50	684.48
November	1144.13	690.53	447.66	684.26
December	1145.28	691.31	447.96	684.17

[3] meters above sea level

Table 4: Actual reservoir elevation levels from LP solution

	Reservoir elevation levels (from LP solution)[masl]			
	Kihansi	Mtera	Kidatu	Nyumba ya Mungu
Starting values	1145.71	698.81	445.52	687.01
End of Month				
January	1145.61	694.85	446.48	687.74
February	1141.06	694.90	445.65	688.23
March	1145.92	695.22	448.61	688.75
April	1145.92	695.33	446.61	688.77
May	1141.06	695.54	445.99	688.71
June	1141.06	695.61	444.62	688.70
July	1141.06	695.72	444.20	688.72
August	1141.06	695.81	446.08	688.74
September	1141.06	695.93	442.88	688.69
October	1141.06	695.99	432.00	688.67
November	1141.06	696.18	436.51	688.70
December	1145.92	696.84	446.62	688.77

year 2000 show that, from the total generated units for the whole year, only 1.31% was to be generated by thermal power plants (compared to 11% which was the actual generation). Although the hydro generation was maximized, still the reservoir levels were also kept to higher levels compared to the actual final levels. That is to say, for the same energy generated in year 2000, if the LP solution was used, the total operation cost would have been low since the usage of thermal power plants was minimized. All the cases tested, showed that; the water in the reservoirs was conserved and maximized at high elevation levels possible, as the linear programming solution maximizes the value of stored water at the end of the planning schedule. For this case, water in the reservoirs was conserved and may be used in the dry seasons. This will decrease the probability of power curtailment and possibility of increasing power price during the dry seasons.

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REFERENCES

1. A.J Wood and B.F Wollenberg, *Power generation, Operation and Control,* John Willey & Sons Publishers, 1996
2. A.P Bonaert, A.H El-Abiad and A.J Koivo, *Optimal Scheduling of Hydrothermal Power Systems*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS - 91, January 1972, pp 263-271
3. EEE Working Group Report, *Description and Bibliography of major Economy-Security Functions, Parts I, II, III*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, January 1981, pp. 211-235
4. J. Nanda and P.R Bijwe, *Optimal Hydrothermal Scheduling With cascaded Plants Using Progressive Optimality Algorithm*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS - 100, No. 4, 1981. pp 2093- 2099.
5. Jianxin Tang and Peter Luh *Hydrothermal scheduling via extended differential dynamic programming and mixed coordination*, IEEE Transactions on Power Apparatus and Systems, Vol. 10, No. 4, November 1995. pp 2021 – 2027

6. N. Mwakabuta, and A. Kyaruzi, *Linear programming applied to short-term planning of a hydro-thermal system*, International Conference on Electrical Engineering and Technology 2001 (ICEET01), Dar es Salaam, Tanzania, September 2001, pp P41

7. Olof Nilson, *Short Term Scheduling of Hydrothermal Power Systems with Integer Hydro Constraints*, Doctorate Thesis, Royal Institute of Technology (K.T.H), 1997.

8. S. Soares and T. Ohishi *Hydro-dominated short-term hydrothermal scheduling via a hybrid simulation-optimization approach a case study*, IEEE Proceedings of Generation, Transmission and Distribution, Vol. 142, No. 6, November 1995. pp 569 – 575.

9. SYRAP Short-term Power System Simulation and Planning Software Manual.