Iranian Journal of Science & Technology, Transaction B: Engineering, Vol. 34, No. B3, pp 325-333
Printed in The Islamic Republic of Iran, 2010

"Research Note"

GENERATION EXPANSION PLANNING FOR IRAN POWER GRID*

M. KHAKBAZAN-FARD[1],** H. HAERI[1], M. PASSAR[1], MOHAMMAD S. NADERI[2] AND P. NARIMISSA[1]

[1]Iran Power Generation, Transmission and Distribution Management Co. (Tavanir), Tehran, Iran
[2]University of New South Wales, Sydney, Australia
Email: m.khakbazan@tavanir.org.ir

Abstract– Generation expansion planning is one of the major modules of power system planning studies, normally performed for the next 10-30 years. Optimal generation expansion planning is a non-linear and limited optimization problem. All solutions are compared to each other in order to reach final optimal solution. Some simplifications are made to reduce the problem dimensions which will not lead to unreal results. In this paper, WASP software package, one of the well known power expansion planning softwares, is used to optimize Iran generation expansion planning. For modeling the power system, WASP uses the probabilistic simulation, while for optimization the dynamic programming method is used. In this paper, the generation system expansion planning is performed from 2009 till 2024 (a duration of 16 years). Finally, the sensitivity analysis is performed on the capital cost and the fuel cost of power plants.

Keywords– Optimal generation expansion planning, WASP software package, sensitivity analysis

1. INTRODUCTION

The main goal of optimal generation expansion planning (OGEP) is to seek the most economical generation expansion scheme achieving a certain reliability level according to the forecast of demand increase in a certain period of time. In OGEP the type and capacity of generating units and the time of investment for new generating units should be determined. Therefore, generation planning is a complicated task. Mathematically, it is a problem with high dimensionality, non linearity and stochastic characteristics.

The present value of the generating unit capital cost and annual operation costs are non-linear functions of decision variables. In addition, some constraints like reliability constraints are also non-linear. Therefore, model of generation expansion planning is actually non- linear.

The basic data required for OGEP like load forecast data, fuel and equipment costs, discount rates, etc., have uncertainties. As a result, the generation planning process is remarkably stochastic in nature [1].

The OGEP has two processes: 1- calculation of generation costs 2- finding the best and most optimized scheme. Because of stochastic factors like demand forecasting, forced outage rate and etc., the calculation of generation cost is both difficult and not precise. In recent years few methods have been proposed to solve the OGEP problem. The probabilistic simulation which concerns stochastic nature is one of them [2].

Each method utilizes a specific algorithm like genetic algorithm [3], [4], intelligent neural network [5], fuzzy logic [6] and recursive Tabu search technique [7]. In addition, according to the increasing

*Received by the editors September 3, 2009; Accepted June 3, 2010.
**Corresponding author

ability of the computation algorithm in new computers, many software packages have been developed to fulfill two tasks, as mentioned below:

1- Simulation of power plant generation

2- Optimization of the generation system.

In general, software uses the probabilistic, Monte-Carlo simulation or equivalent capacity method to model the generation system expansion.

The most applicable way to find the optimized model is dynamic programming, yearly optimization and linear/non-linear programming. WASP IV is one of the strongest softwares that has been introduced according to the order of the International Atomic Energy Agency (IAEA) and uses the probabilistic simulation for power generation simulation. In this software, probability of outage rate of power plants is considered in the Load Duration Curve and by Fourier series the curve is approximated [8].

2. MATHEMATICS OF OGEP

In OGEP, the combination of power plants is acceptable when it not only supplies the load, but also has the minimum cost. So the objective function is defined as follows [9]:

$$B_j = \sum_{t=1}^{T} \bar{I}_{j,t} - \bar{S}_{j,t} + \bar{L}_{j,t} + \bar{F}_{j,t} + \bar{M}_{j,t} + \bar{O}_{j,t} \tag{1}$$

where:

B_j	Objective function
I	Depreciable capital investment cost
S	Salvage value of investment cost
F	Fuel cost
L	Non-depreciable capital investment cost
M	Maintenance cost
O	Cost of energy not served

't' is one of the years and T is the length of study period.

The bar over the symbols has the meaning of discounted values to a reference date at a given discount rate 'i' [9].

WASP software analysis requires a starting point to determine the alternative expansion policies of the power system. If $[K_t]$ is a vector containing the number of all generating units which are in operation in year t for a given expansion plan, then $[K_t]$ must satisfy the following relationship [9]:

$$[K_t] = [K_{t-1}] + [A_t] - [R_t] + [U_t] \tag{2}$$

where:

$[A_t]$ is the vector of committed additions of units in year t,

$[R_t]$ is the vector of committed retirements of units in year t,

$[U_t]$ is the vector of candidate generating units added to the system in year t,

$[A_t]$ and $[R_t]$ are given data, and $[U_t]$ is the unknown variable to be determined and is called the system configuration vector.

3. PROBLEM CONSTRAINTS

OGEP has some constraints. Three constraints have been considered in this study.

a) Reserve margin

Defining the critical period (p) as the period of the year for which the difference between the corresponding available generating capacity and the peak demand has the smallest value, and $P(K_{t,p})$ as installed capacity of the system in the critical period of year t, the following constraints should be met by every acceptable configuration:

$$(1+a_t)D_{tp} \geq P(K_{tp}) \geq (1+b_t)D_{tp} \tag{3}$$

which simply states that the installed capacity in the critical period must lie between the given maximum and minimum reserve margins, a_t and b_t respectively, above the peak demand $D_{t,p}$ in the critical period of the year.

b) Reliability of system configuration

Reliability of the system is evaluated in terms of the Loss of Load Probability (LOLP) index. So each acceptable configuration must respect the following constraint:

$$\text{LOLP}(t) < C_t \tag{4}$$

where, C_t is a limitation factor.

c) Construction limit

The number of plants that can be constructed in each year is definite so that every acceptable configuration must respect:

$$[U_t^O] \leq [U_t] \leq [U_t^O] + [\Delta U_t] \tag{5}$$

where $[U_t]$ is the configuration vector, $[U_t^0]$ is the smallest value permitted to the configuration vector and $[\Delta U_t]$ is the tunnel constraints (the maximum permitted candidate that can be added each year).

4. ENERGY-NOT-SERVED

If an expansion plan contains a system configuration for which the annual energy demand E_t is greater than the expected annual generation G_t of all units existing in the configuration for the corresponding year t, the total costs of the plan should be penalized by the resulting cost of the energy-not-served. Obviously, this cost is a function of the amount of energy-not-served N_t, which can be calculated as [9]:

$$N_t = E_t - G_t \tag{6}$$

The cost of energy not-served is calculated as follows [9]:

$$C(E_s) = C_1 + C_2\left(\frac{E_s}{EA_j}\right) + C_3\left(\frac{E_s}{EA_j}\right)^2 \tag{7}$$

where E_s is the amount of energy-not-served (GWh), EA_j is the demand energy in year j (GWh), $C(E_s)$ relates the incremental cost of energy not-served to the amount of energy not-served which is calculated as $\$/kWh$.

5. THE OGEP FOR IRAN POWER GRID

The period of study is from 2009 until 2024. Each year is divided into four periods. This division has no effect on thermal power plants but it is important for hydro power plants because of the effect of seasons on the generation of hydro power plants.

a) Input data preparation

1. Power system load: The first necessary data is the annual peak load, period peak load and shapes of each period Load Duration Curve (LDC). Input data is prepared using normalized load duration curve of the period, which can be expressed either in the form of a fifth-order polynomial, or in a discrete form by points (load magnitude and load duration) of the curve. WASP software calculates the Fourier series coefficients and integration of the surface determines the load factor and energy demand.

2. Existing Power Plants Specifications: Technical and economical characteristics of existing and approved thermal, hydro and pump-storage power plants should be introduced to the software.

3. Candidate Power Plants Specifications: Since the object is to find an optimal expansion plan, it is necessary to introduce the candidate plants to the software. So, according to Iranian conditions, four types of plants are chosen: 1- Steam power plant (S325), 2- Combined Cycle power plant (CC), 3- Gas turbine power plant operated during peak load (G13P), and 4- Gas turbine power plant (G13B) operated during base load. Characteristics are shown in Table 1.

Table 1. Characteristics of candidate power plants

Characteristic	S325	CC	G13P	G13B
Min operating level in each year [MW]	163	200	0	65
Max generating capacity in each year [MW]	325	400	100	130
Forced outage rate [%]	7.8	6.7	7.53	6.12
Scheduled maintenance days per year	56	42	35	40
Fixed O&M cost [$/kW-month]	0.61	0.282	0.456	0.166
Variable O&M cost [$/MWh]	0.410	0.363	0.725	0.587

Information about the candidate power plants is extracted from the existing new approved plants' contract.

Using this specification, WASP calculates the cost of generation for each plant during peak load and base load and according to that specified economic loading order (Table 2).

Table 2. Unit generation cost ($/MWh)

Name	Base Domestic	Base Foreign	Full load Total
S325	0.4	32.9	28.5
G13P	0.7	74.1	74.8
CC40	0.4	40.7	35
G13B	0.6	61.7	49.1

b) Simulation of the system

WASP software uses the probabilistic simulation method for analyzing and comparing different configurations. It also compares LOLP and reserve capacity with the amount specified by the user. LOLP has been chosen one day per year equivalent to 0.274 %. Minimum and maximum reserve margin are chosen 5% and 40%, respectively. The software prepares a primary configuration with regard to the limitations and determines the amount of energy that each of the power plants can supply according to their outage rate.

c) Economic parameters

One of the most important economic parameters is discount rate, which is chosen 10% for both foreign and domestic investment and maintenance. The escalation rate is 0%. According to the latest studies in Iran, energy-not-served cost is 1.1 $\$/_{kWh}$.

For calculating the objective function, depreciable and non depreciable capital costs ($\$/_{kW}$) should be determined.

In addition, if the capital cost is \$A and the construction time is N years, the capital investment cost should be distributed over the construction period according to a specific cash flow and the Interest During Construction (IDC) should be contemplated. Table 3 shows the capital investment costs and IDC for the candidate power plants.

Table 3. Capital Investment costs and IDC for Candidate Power Plants

Name	Depreciable capital cost (\$/kW)		IDC (%)
	Domestic	Foreign	
S325	370.11	442.65	19.21
G13P	0.1	374.78	8.08
CC40	135.36	541.11	15.63
G13B	0.1	374.78	8.08

In this study, the construction period for steam power plants is considered 5 years, for gas plants is 2 years and for combined cycle plants is 4 years. For calculating the salvage value, the sinking fund depreciation method is used because in this method the interest rate is concerned. Table 4 shows the considered costs of different fuel types (Natural Gas, Gasoil, HFO) which are used for existent and future power plants.

Table 4. Fuel cost (Average of last 5 years for Persian Gulf F.O.B)

Type	price
Natural Gas	690 Rials/m^3
Gasoil	0.47 \$/lit
HFO	0.27 \$/lit

6. STUDY RESULTS

Optimal generation expansion plan for the Iran power grid is gained using technical and economical characteristics of the input power plant and the final configuration is shown in Table 5. It should be mentioned that the power supplys which are under construction are considered. In this table, the second column is objective function, which is described in K\$. It is the sum of investment, O&M and fuel cost in each year based on the number of power plants as expressed in Eq. (1). Column 3 is the amount of LOLP in each year, and the next columns show the number of power plants which the software has chosen as candidates in order to optimize the power generation system.

As can be seen, for supplying the base load, steam power plants are chosen. The main reason is the lower price of the fuel of steam plants (9 months Gas and 3 months HFO) in comparison to the fuel of gas and combined cycle power plants (9 months gas and 3 months gasoil). In spite of the higher capital investment for steam power plants in comparison to combined cycle and gas power plants, the software has chosen the steam power plants which show the significance of the operation and maintenance costs in the objective function. In addition, the software has chosen peak gas plants for supplying the peak load (the number of plants in each year is cumulative). It should be mentioned that the power supplies which are under construction are considered in the program, so between the years 2009 and 2015, software has not chosen any candidate.

Table 5. Optimum configuration of the Iran power generation system

Year	OBJ.FUN	LOLP(%)	S325	G13P	CC40	G13B
2024	68935312	0.268	65	62	0	0
2023	66460444	0.266	55	61	0	0
2022	63807100	0.264	45	60	0	0
2021	60969176	0.266	35	59	0	0
2020	57962352	0.264	27	52	0	0
2019	54734960	0.274	17	51	0	0
2018	51401424	0.256	12	35	0	0
2017	47945856	0.266	11	5	0	0
2016	44227072	0.262	4	3	0	0
2015	40464604	0.074	0	0	0	0
2014	36855052	0.005	0	0	0	0
2013	33052598	0.001	0	0	0	0
2012	29055858	0.001	0	0	0	0
2011	24583090	0.001	0	0	0	0
2010	19797508	0.200	0	0	0	0
2009	14959247	0.030	0	0	0	0

7. SENSITIVITY ANALYSIS

In the following, the sensitivity analysis on the capital investment cost of steam power plants has been implemented. With a 50% increase on the investment of steam power plants, the final configuration changes a little and the four combined cycle plants have been added by the software (Table 6). Table 7 shows the relationship between the changes in the capital investment cost in percent and the number of power plants. As can be seen there are no considerable changes in the generation system configuration when the capital investment of the steam power plant is increased up to 50 percent.

At the next stage, the cost of HFO (a portion of fuel of steam power plants) has increased but the result has not changed noticeably. The result has been shown in Table 8.

Table 8 shows that in the year 2024 only 5 combined cycle power plants are added to the final configuration, while the number of steam power plants is 59 plants. Table 9 depicts the relationship between the changes in the HFO price and the generation system configuration. It shows that increasing the HFO price has no noticeable effect on the results.

Table 6. Sensitivity analysis: 50% increase in the capital investment cost of steam power plants

year	OBJ.FUN	LOLP(%)	S325	G13P	CC40	G13B
2024	70812480	0.273	59	65	4	0
2023	68336600	0.270	54	60	1	0
2022	65638772	0.264	45	60	0	0
2021	62708392	0.266	35	59	0	0
2020	59588112	0.264	27	52	0	0
2019	56164796	0.274	17	51	0	0
2018	52689612	0.256	12	35	0	0
2017	49118852	0.272	10	8	0	0
2016	45180080	0.262	4	3	0	0
2015	41195104	0.074	0	0	0	0
2014	37515372	0.005	0	0	0	0
2013	33634732	0.001	0	0	0	0
2012	29550814	0.001	0	0	0	0
2011	24993434	0.001	0	0	0	0
2010	20112752	0.200	0	0	0	0
2009	15167649	0.002	0	0	0	0

Table 7. Sensitivity analysis: relationship between the changes of the capital investment cost of steam power plants and the final optimum power generation system

Investment cost increase [%]	10				30				40				50			
Candidates	S325	G13P	CC	G13B	S325	G13P	CC	G13B	S325	CC40	G13B	G13P	S325	CC	G13B	G13P
Cumulative No.	65	62	0	0	65	62	0	0	63	69	0	0	59	65	4	0
Capacity (per unit)	0.773	0.227	0	0	0.773	0.227	0	0	0.747	0.253	0	0	0.703	0.238	0.058	0

Table 8. Sensitivity analysis: power generation system configuration after 25% increase in HFO price

Year	OBJ.FUN.	LOLP(%)	S325	G13P	CC40	G13B
2024	72040584	0.273	59	61	5	0
2023	69376000	0.274	53	59	2	0
2022	66528784	0.273	43	58	2	0
2021	63502228	0.271	34	58	1	0
2020	60310700	0.269	26	51	1	0
2019	56908944	0.274	17	51	0	0

Table 8 Continued.

2018	53407708	0.256	12	35	0	0
2017	49792004	0.266	11	5	0	0
2016	45910464	0.262	4	3	0	0
2015	41993872	0.074	0	0	0	0
2014	38241152	0.005	0	0	0	0
2013	34297716	0.001	0	0	0	0
2012	30182670	0.001	0	0	0	0
2011	25584470	0.001	0	0	0	0
2010	20651704	0.200	0	0	0	0
2009	15623066	0.030	0	0	0	0

Table 9. Sensitivity analysis: relationship between the changes of HFO price and the final optimum power generation system

Increase in HFO Price [%]	10				15				20				25			
Candidates	S325	G13P	CC	G13B	S325	G13P	CC40	G13B	S325	CC	G13B	G13P	S325	CC	G13B	G13P
Cumulative No.	62	64	2	0	62	64	2	0	62	64	2	0	59	61	5	0
Capacity (per unit)	0.736	0.234	0.029	0	0.736	0.234	0.029	0	0.736	0.234	0.029	0	0.703	0.223	0.073	0

8. CONCLUSION

In this study, Iran power generation planning was optimized using WASP IV package. The planning process was performed between the years 2009 and 2024, and the final optimized results were shown in Table 5 through Table 9. In the first step, an optimal generation expansion plan was extracted, and to supply the base load, steam power plants were chosen because of their lower fuel costs in comparison with the other candidate power plants. It revealed the significance of the operation and maintenance costs in the objective function. Further, the sensitivity analysis was performed on capital cost as well as the fuel cost of steam power plants which did not result in any significant change. In other words, steam power plants are the most appropriate candidates for supplying the base load due to their technical and economical characteristics.

REFERENCES

1. Wang, X. & Mcdonald, J. R. (1994). *Modern power system planning*. McGraw-Hill Publication.
2. Dehaghin, M., Parsa Moghadam, M. & Javidi, M. (ICEE2004). Power planning generation with genetic algorithm. *12th Iranian Conference of Electrical Engineering.*
3. Park, J., Park, Y. & Won, J. (2000). An improved genetic algorithm for generation expansion planning. *IEEE Trans. on Power System*, Vol. 15, Issue 3, pp. 916 – 922.

4. Kannan, S., Baskar, S., McCalley, J. D. & Murugan, P. (2009). Application of NSGA-II algorithm to generation expansion planning. *IEEE Trans. on Power System*, pp. 454-461.
5. Zhu, J. & Chow, M. (1997). A review of emerging techniques on generation expansion planning. *IEEE Trans. on Power System,* Vol. 12, pp. 1722-1728.
6. Su, Ch., Lii, G. & Chen, J. (2000). Long-term generation expansion planning employing dynamic programming and fuzzy techniques. *Industrial Technology 2000, Proceedings of IEEE International Conference*, Issue, pp. 644-649, Vol. 2, pp. 19-22.
7. Seyed-Hoseini, S. M. & Jenab, K. (2004). The development of the TABU search technique for expansion policy of power plant centers over specific defined reliability in long range planning. *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 28, No. B2.
8. Movahed, M. (1995). The scientific base of generation expansion planning. *Generation Deputy*, TAVANIR
9. Wien Automatic System Planning (WASP) Package, (2006). WASP-IV User's Manual. *IAEA*.