Generation Expansion Planning Considering the Equilibrium Between System Reliability and Cost: A Pakistani Case Study

Akif Zia Khan, Sun Yingyun, Ahsan Ashfaq, and Sarmad Majeed Malik

***Abstract*—**Pakistan is experiencing the worst energy shortfall of its history with energy shortfall exceeding 6000 MW by 2013.Power outages, excessive hours of load shedding and service interruptions have adversely affected the economic growth of the country and has imparted unemployment and lawlessness to the society. The loss incurred by industrial sector alone due to unreliable and interrupted power supply was estimated at Rs 157 billion. In addition to the power outages, Pakistan produces about 67 % of its electricity from energy guzzling furnace oil and natural gas fired power plants which accounts for the hefty electricity tariff in Pakistan. Electricity sector in Pakistan needs structural overhauling and rampant increase in generation on war footing basis to meet the economic goals of the country. To address the aforementioned issues, this paper considers the cost of unserved energy (COUE) in Generation expansion planning (GEP) problem of Pakistan as an index of reliability evaluation and presents a model that help to maintain the equilibrium between system cost and reliability. The model is implemented in MATLAB using Genetic Algorithm and is applied to a case study of Pakistan. The results suggest that implying an extra cost of Rs 11.5 per Kwh as COUE to the existing tariff will help to achieve reasonable reliability level at affordable cost.

***Keywords*—**Generation expansion planning(GEP), Cost of unserved energy(COUE), Energy not served(ENS), Willingness to pay(WTP), Power Reserve Margin(PRM), Loss of load probability(LOLP)

I. Introduction

PAKISTAN is facing severe energy crisis. Inadequate energy supply, costly generation mix, aging infrastructure, escalating circular debt and lack of service reliability are among the major challenges faced by Pakistani power system. Service interruptions caused by long hour load shedding are hampering the economic growth of the country and are making the life of common man miserable. For the last two decades, the power system in Pakistan has struggled to maintain acceptable reliability level of supply at affordable tariff. Elevation of reliability level requires network up gradation, retrofitting of existing plants, curtailment of network losses and installation of new power plants. The provision of all such facilities to increase the reliability level comes at an extra price which adds to the ordeal of consumers.

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The most widely accepted term for the evaluation of reliability level of a generation system is energy not served (ENS).Energy may not be served to the consumers on account of inadequate capacity or fault occurrence causing the power outage. Monetary evaluation of the loss to consumers due to power outages and adding the extra cost of unserved energy (COUE) in the generation expansion planning model can help to improve the reliability level of supply. The loss incurred due to power outages depends upon the duration, frequency and time of incidence of outage. Also the loss bore by different types of consumers is different and depends upon their consumption of energy. For example the loss caused to a residential consumer by the power outage would only be the loss of leisure activities while an industrial consumer will have to bear the spoilage cost, adjustment cost and the loss of labor hours for service interruption. Also in the event of unscheduled interruptions, the losses due to power outages are increased because consumers are unable to arrange the alternatives for restoration of supply.

This paper applies willingness to pay (WTP) approach in Pakistan to obtain the consumers willingness for paying extra amount (Rs/Kwh) to avoid power outages and enjoy uninterrupted supply. This cost is integrated in the generation expansion planning model as cost of unserved energy and is modeled as a function of energy not served (ENS).

The paper proceeds as follow. Section II presents brief literature review. Section III describes the power system in Pakistan. Section IV discusses the mathematical model. Algorithm developed to solve the model is presented in section V. Section VI contains results and discussions. Section VII summarizes and concludes the paper.

II. Literature review

In the past a number of studies have been conducted for the monetary valuation of losses caused by power outages in Pakistan. Each of these studies adopted different methodologies for the evaluation of costs and were carried out aiming a particular type of consumer. Reference [1] discussed the impact of power load shedding to domestic consumers in Pakistan and determined the consumer's willingness to pay extra amount to avoid power outages. Adopting survey based approach and considering the utility loss, extra cost of self generation and other losses incurred;

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the authors evaluated Rs 11 per Kwh as the average cost of power outages for domestic consumers belonging to different income group. The results of the study also showed that inadequate capacity and poor reliability level of energy supply results in an annual loss close to 200 billion rupees to the domestic consumers. Reference [2] evaluated the costs of power outages to industrial consumers in Pakistan. Based on the survey conducted in 115 industrial units installed in four major industrial cities of Pakistan, the authors estimated that the industrial sector each year faces a loss of more than Rs 210 billion because of power outages. Power load shedding also results in the loss of over US$ 1 billion of export earnings and unemployment of 400,000 workers. Reference [3] attempted to evaluate the cost of unserved energy in Pakistan. The results of the study suggest that industrial consumers are the worst affected type of consumers losing up to 37 percent of their output because of power outages. Reference [4, 5] made an attempt to evaluate the loss of industrial output caused by outages in India and Zimbabwe respectively. Reference [6] stated that loss incurred by different types of consumers due to power outages varies greatly therefore a unified consumer loss function (UCLF) is required to quantify the losses which can be justified for all types of consumers. UCLF was based on the outage duration and energy consumption of each type of consumer.

From the literature review conducted, it was found that till date work was done on the quantization of losses caused by power outages to different types of consumers but no work was done on integrating this cost in the Generation Expansion Planning (GEP) problem. This paper aims to develop a GEP model for Pakistan incorporating the cost of unserved energy as an index for reliability evaluation. Increasing the reliability level of supply results in additional cost to the consumers however determining the optimal point of reliability/cost curve can help to maintain reliable supply of electricity at affordable cost.

III. Power sector in pakistan

The power sector in Pakistan is mainly administered and governed by three entities i.e. Water and Power Development Authority (WAPDA), Pakistan Electric Power Company (PEPCO) and Karachi Electric Supply Company (KESC).WAPDA is responsible for running, maintaining and developing all the hydropower projects. PEPCO comprising of 9 distribution companies (DISCOs), 4 generation companies (GENCOs) and national transmission dispatch company (NTDC) manages generation, transmission and distribution of power in whole country except the southern city of Karachi, the largest city and financial hub of Pakistan. KESC having its own generation, transmission and distribution capabilities supplies power to the consumers of Karachi [7].

The power sector in Pakistan has been engulfed by severe energy crisis for the last two decades. The swelled up energy shortfall of 4500-6000 MW is causing load shedding of 8-12 hours in rural and urban areas. Industrial units are operating under their rated production capacity and this inadequate supply of energy is crippling the economy of the country. Reduced generation capacity of existing units, bad governance, escalating line loses, seasonal variation of hydropower plants and circular debt of more than 400 billion rupees are some of the reasons contributing to the energy crisis in Pakistan. Another quandary faced by power sector is the imbalance generation mix which accounts for the costly generation of electricity. The contribution of different energy carriers for power production in Pakistan is presented in Table 1[7].

TABLE I
CONTRIBUTION OF DIFFERENT ENERGY CARRIERS FOR POWER PRODUCTION

Energy Carrier	Contribution (%)
Gas	29.4
Oil	37.8
Hydro	29.4
Nuclear	3.02
Coal	0.1

Pakistan having third largest coal reserves in the world with reserves estimated about 175 billion tons in Thar Coal field can produce cheap electricity from coal instead of relying heavily on oil which country needs to import from international market [8].Also Pakistan has tremendous potential of Renewable energy sources which country needs to harness in order to produce cheap electricity which will help to overcome the energy crisis, better the reliability level of supply and lower the soaring energy tariff.

Domestic sector being the biggest consumer of electricity in Pakistan with consumption of about 46 % bears the brunt of power outages. The consumption of electricity by different consumers is presented in Table II.

TABLE II
ELECTRICITY CONSUMPTION BY SECTORS

Sector	%
Domestic	46
Industrial	26.6
Agriculture	13
Commercial and Bulk supply	13.4

Tariff determination for domestic consumers is made on the basis of incremental block tariff (IBT) structure. In this approach, different slabs of tariff are made depending on the electricity consumption of consumers. The underlying principle for applying this approach is to give relief to the impoverished consumers also known as lifeline consumers whose monthly consumption is less than 50 units. The tariff structure of residential consumers in Pakistan is presented in Table 3 [1].

TABLE III
TARIFF STRUCTURE FOR RESIDENTIAL CONSUMERS

Slab (units)	Tariff(Rs/Kwh)
0-50	2.00
51-100	5.79
101-300	8.11
301-700	12.33
Above 700	15.07

The energy consumption of each block is presented in fig 1.

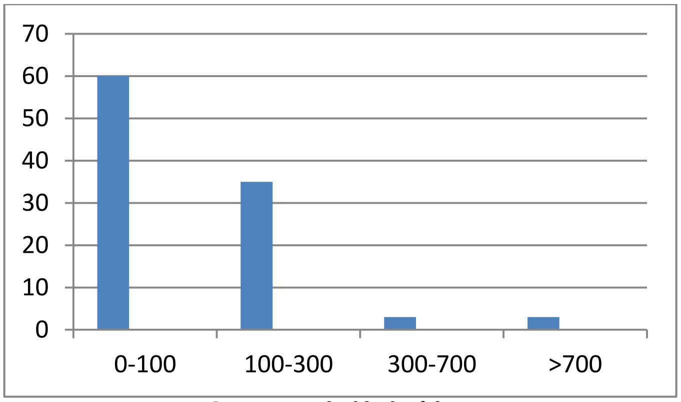

Fig 1 Energy Consumption by block of domestic consumers

Lifeline consumers consume more than 60% of electricity among the domestic consumers and enjoy the generous subsidy of more than Rs 9 per Kwh. Because of the subsidy offered by government, the relation between reliability and cost of supply can be justified for domestic consumers. However industrial sector being the second largest consumer of electricity neither enjoys any subsidy nor uninterruptible supply and bears each year loss of billions of rupees due to power outages. The economic cost of outages stands much higher than the high power tariff for industrial consumers. The findings of [3] suggest that industrial consumers are willing to pay Rs 11.5 per Kwh as cost of unserved energy (COUE) to avoid power outages. Since industrial units have to pay for either self generation or bear the outage loss, this extra cost on the power tariff is still economically viable to them to improve the reliability of supply. This extra cost imposed on the tariff can help to maintain the equilibrium between reliability and cost of supply. This paper integrates this cost in the generation expansion planning model as a mean to improve the reliability of supply.

IV. MATHEMATICAL MODEL

The GEP model developed in this section aims to optimize the reliability cost curve in order to enhance the reliability of supply to industrial consumers at an affordable price. It is estimated that any investment in generation expansion and revamping existing units can be recovered in a short span of time because of the high cost of power outages to industrial consumers. For reliability maximization, the model considers spinning reserves of greater than 20 percent of the peak load in the system and considers only coal fired, hydro and nuclear power plants as candidate units for fleet expansion because of their cheap operation , better capacity factor and lower forced outage rates. These new units will add cheap electricity in the system and will help to improve the reliability of supply. The suggested model evaluates the type and number of new power plants so that current and future electricity demands are met while maximizing the reliability and minimizing the cost.

A. Objective Function

The objective function comprises of minimizing the cost of fleet expansion while maximizing the reliability. Three reliability indices i.e Loss of load probability (LOLP), Peak Rerve margin (PRM) and energy not served (ENS) are considered in the constraints of model for reliability evaluation. Total cost, C_{total}, to be minimized over the planning horizon is given by (1).

$$C_{total} = C_{inv} + C_{fuel} + C_{O\&M} + C_{COUE} \qquad (1)$$

Where

C_{inv} The investment cost

C_{fuel} The fuel cost

$C_{O\&M}$ The operation and maintenance cost

C_{COUE} The cost of unserved energy

These cost parameters are considered for the existing units as well as the candidate plants

1) Investment Cost

The levelised investment cost for creating a new power plant in terms of Rs/MWh is modeled by (2)

$$C_{inv}^{N} = \sum_{t=1}^{T}\sum_{i\in N}(I_{it}.P_i^N.\omega_{it}.CF_i^N.h_i^N) \qquad (2)$$

Where, I_{it} is the investment cost of unit type i installed in year t, P_i^N is the capacity of new power plant of type i in MW, ω_{it} is the number of unit type i required in year t. Its discrete decision variable and 1 means unit capacity, CF_i^N is the capacity factor of unit type i of new power plants and h_i^N is the average annual utilization hours of unit type i of new power plants

2) Fuel Cost

The fuel cost of new and existing power plants in terms of Rs/MWh is modeled by (3) and (4).It is assumed that fuel costs remain constant throughout the planning horizon.

$$C_{fuel}^{N} = \sum_{t=1}^{T}\sum_{i\in N}(F_{it}^N.P_i^N.\omega_{it}.CF_i^N.h_i^N) \qquad (3)$$

$$C_{fuel}^{E} = \sum_{t=1}^{T}\sum_{i\in E}(F_{it}^E.P_i^E.CF_i^E.h_i^E) \qquad (4)$$

Where, F_{it}^N is the fuel cost (Rs/MWh) for unit type i of new power plants in year t, F_{it}^E is the fuel cost (Rs/MWh) for unit type i of existing power plants in year t and h_i^E is the average annual utilization hours of unit type i of existing power plants

3) Operation and Maintenance Cost

Operation and Maintenance (O & M) of new and existing power plants in terms of Rs/MWh is modeled by (5) and (6).O&M costs consist of fixed and variable terms. Here only variable term is considered and it is assumed to remain constant throughout the planning period

$$C_{O\&M}^{N} = \sum_{t=1}^{T}\sum_{i\in N}(O_{it}^N.P_i^N.\omega_{it}.CF_i^N.h_i^N) \qquad (5)$$

$$C_{O\&M}^{E} = \sum_{t=1}^{T}\sum_{i\in E}(O_{it}^E.P_i^E.CF_i^E.h_i^E) \qquad (6)$$

Where, O_{it}^N is the Operation and Maintenance cost (Rs/MWh) for unit type i of new power plants in year t and

O_{it}^{E} is the Operation and Maintenance cost (Rs/MWh) for unit type i of existing power plants in year t

4) Cost of unserved energy

Cost of unserved energy as a function of energy not served is given by (7)

$$C_{COUE} = \sum_{t=1}^{T}(COUE.ENS) \quad (7)$$

Where COUE is the cost of unserved energy in Rs/Kwh and ENS is the energy not served

The GEP problem to be considered is mathematically formulated after combining (2) - (7) as follows

$$\begin{aligned} minf(i,j,t) = & \sum_{t=1}^{T}\sum_{i\in N}(I_{it}.P_i^N.\omega_{it}.CF_i^N.h_i^N) + \\ & \sum_{t=1}^{T}\sum_{i\in N}(F_{it}^N.P_i^N.\omega_{it}.CF_i^N.h_i^N) + \\ & \sum_{t=1}^{T}\sum_{i\in E}(F_{it}^E.P_i^E.CF_i^E.h_i^E) + \\ & \sum_{t=1}^{T}\sum_{i\in N}(O_{it}^N.P_i^N.\omega_{it}.CF_i^N.h_i^N) + \\ & \sum_{t=1}^{T}\sum_{i\in E}(O_{it}^E.P_i^E.CF_i^E.h_i^E) + \\ & \sum_{t=1}^{T}(COUE.ENS) \end{aligned} \quad (8)$$

B.Constraints

The GEP optimization problem is subject to the following constraints:

1) Annual Energy Demand Constraint

$$\sum_{i\in N}(P_i^N.\omega_{it}.CF_i^N.h_i^N) + \sum_{i\in E}(P_i^E.CF_i^E.h_i^E) \geq L_t.H_t \quad (9)$$

Where, L_t is the peak load in year t and H_t is the utilization hours of load in year t

2) Peak Reserve margin Constraint

$$\sum_{i\in N}(P_i^N.\ \omega_{it}.\rho_N) + \sum_{i\in E}(P_i^E.\rho_E) \geq L_t(1+R_t) \quad (10)$$

Where, ρ_N is availability rate of the new generation unit at peak and ρ_E is availability rate of the existing generation unit at peak load and R_t is the peak spinning reserve requirement of the system in year t

3) Upper and Lower Bound Constraints

$$\omega^{\min}{}_{i(t-1)} \leq \omega_{it} \leq \omega^{\max}{}_{i(t+1)} \quad (11)$$

4) Reliability Constraint

$$Lp_t \leq \overline{Lp} \quad (12)$$

Where, Lp_t is the loss of load probability in year t and $\overline{Lp}$ is the maximum acceptable level of loss of probability. Constraints 2 and 4 are used as an index of reliability evaluation

This paper applies the genetic algorithm(GA) to solve the model.GA has been successfully applied to solve the GEP problem.

V. Algorithm Applied To Get Solution

Treating the new generating units as genes and applying GA, the following algorithm is applied to solve the problem

Step 1: Gather the necessary data needed by the algorithm

Step 2: Initialize the random population and testing the feasibility of the genomes

Step 3: Evaluating the score of each genome in the population and then using the genomes with best fitness values in the current population as parents and applying different operators on them to get the children of next generation. Children are generated either by making arbitrary changes to a single parent i.e. mutation or by combining the vector entries of a pair of parents i.e. crossover. Children thus generated form the new generation

Step 4: Repeat step 3 to create new generations. The algorithm stops when the maximum number of generations set in the algorithm is reached. Output the solution

VI. Results and Discussion

The proposed GEP model developed in section IV is applied to a case study of Pakistan for a 6-year planning horizon starting from 2015 and ending in 2020. The candidate plants for fleet expansion include coal, hydro and nuclear power plants. These plants are considered for fleet expansion because of their cheap operation and higher capacity factor as compared to other power plants. Gas fired power plants are neglected because of the depletion of gas reservoirs in the country. The long term load forecast results of the planning area are presented in Table 4.The technical and economical data for candidate plants taken from [9,10] is presented in Table V.

TABLE IV
LONG-TERM LOAD FORECAST RESULTS

Year	2015	2016	2017	2018	2019	2020
Annual Peak Load Demand (MW)	4580	5645	6775	7550	8340	9249
Annual Energy demand (GWh)	26289	32204	40243	46621	53459	61459

TABLE V
FINANCIAL DATA OF CANDIDATE POWER PLANTS

Power Plant	Capital Cost ($/kW)	Variable O&M including fuel ($/MWh)	Fixed O&M Cost ($/MWh)	Capacity Factor	F.O.R
COAL	65.7	29.2	4.1	.80	.04
NUCLEAR	83.4	12.3	11.6	.95	.12
HYDRO	78.1	6.1	4.1	.98	.07

For existing plants, the case study considers the existing units of IEEE Reliability system (RTS) [11].The technical data of existing units of RTS is presented in Table VI.

TABLE VI
TECHNICAL DATA FOR EXISTING UNITS OF RTS

UNIT SIZE (MW)	Number of Units	Forced Outage Rate	Scheduled Maintenance (wks/year)
12	5	0.02	2
20	4	.10	2
50	6	0.10	2
76	4	0.02	3
100	3	0.04	3
155	4	0.04	4
197	3	0.05	4
350	1	0.08	5
400	2	0.12	6

Three scenarios are considered in this paper targeting three reliability levels. i.e. Highly reliable scenario with LOLP value 0.001, moderately reliable scenario with LOLP value 0.02 and a less reliable scenario with LOLP value 0.07.All newly generated units are added by 100 MW per unit. The results of the three scenarios are presented in Table VII, VIII and IX respectively.

TABLE VII
INSTALLED CAPACITY OF NEW UNITY FOR HIGHLY RELIABLE SCENARIO CORRESPONDING TO LOLP VALUE 0.001

Unit Type	2015	2016	2017	2018	2019	2020
Coal (MW)	400	600	700	900	1100	1300
Nuclear (MW)	200	300	300	500	700	800
Hydro (MW)	0	0	100	200	200	300

TABLE VIII
INSTALLED CAPACITY OF NEW UNITS FOR MODERATELY RELIABLE SCENARIO CORRESPONDING TO LOLP VALUE 0.02

Unit Type	2015	2016	2017	2018	2019	2020
Coal (MW)	300	400	500	600	700	1000
Nuclear (MW)	100	200	200	400	500	700
Hydro (MW)	100	100	300	400	400	400

TABLE IX
INSTALLED CAPACITY OF NEW UNITS FOR LESS RELIABLE SCENARIO CORRESPONDING TO LOLP VALUE 0.07

Unit Type	2015	2016	2017	2018	2019	2020
Coal (MW)	200	300	500	700	800	9000
Nuclear (MW)	100	300	400	700	800	1000
Hydro (MW)	300	400	600	600	700	900

The selection of candidate units in different scenarios is made on the basis of reliability level of each unit and the cost of their operation. The nuclear and coal fired power plants dominate the high and moderate reliability scenarios because of their high availability rates and lower F.O.R. Resultantly the cost of fleet expansion for first two scenarios was high but less for the third scenario. More reliable units are added in the high reliability scenario to meet the required LOLP values .The cost of fleet expansion and the expected energy not served for each scenario is presented in Table X.

TABLE X
EENS AND OPTIMAL COST FOR EACH SCENARIO

Scenario	LOLP Value	EENS(MWh)	Cost (10^9 Rs)
High Reliability Level	0.001	862	1.8956
Moderate Reliability Level	0.02	38560	1.4867
Less Reliability Level	0.07	98652	1.1235

The above table depicts the tradeoff between system cost and reliability level. To meet the desired reliability level, more units are added in the fleet which lowers the LOLP value but increases the system cost. As the system reliability level increases resultantly the EENS value decreases. The results depict that integrating the cost of unserved energy on the basis of WTP approach in GEP problem and setting adequate peak reserve margin and LOLP values in the system can help to achieve require reliability levels at affordable cost.

The study considered deterministic techniques to evaluate the reliability level of system and system adequacy. However the results of the study can be improved by using stochastic techniques such as Z-method for the determination of system reliability level.

VII. CONCLUSION

This paper discusses the dilemma faced by the power sector in Pakistan and the different factors responsible for it. The economic cost of power outages to different types of consumers is also discussed in this paper. Based on the willingness to pay approach, cost of unserved energy is integrated in the GEP model to increase the reliability level of supply so that power outages can be avoided. Three types of scenarios are considered in this study to apply the model corresponding to three reliability levels. The results suggest that integrating cost of unserved energy in the GEP model can serve as an important policy tool to improve the reliability level of the system. Although the improvement in reliability level comes at an extra cost but compared to the economic costs of power outages this cost in fleet expansion can be recovered in a very short span of time. The paper also recommends some stochastic techniques to be considered to improve the results of the study and determine the system adequacy.

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