Optimization of Electric Power Generation for Expansion Planning and Cost-Saving Using Decomposition Techniques: A Case of Developing Countries

S. L. Braide, D.C. Idoniboyeobu

Abstract-This paper formulated the framework of optimization of electric power generation for expansion planning and cost saving. The inability of the power systems in developing countries to generate enough electric power has led to extra-ordinary power losses on the line due to the over load dependence thereby making the power system planning and running cost outrageous. This paper considered the application of decomposition techniques for an optimization search in order to break-down the capacity allocation (that is, the forecasted load or energy demand for twenty (20yrs) projection was determined, which served as the input data for the capacity allocation to the generating stations especially in a developing country like Nigeria, include the following capacities of generating stations:2250MW Afam power, 2350MW Sapele power and 3000MW to Egbin power as expected power to be generated from these stations). The paper examined the existing capacity of the generating stations and considered a capacity-mix combination as: (200MW, 250MW and 300MW) which served as the input data: row-element matrix while the column-element matrix need to be determined or factor-out into different number of unit combination arrangement to achieve different options for the best selection. Five optimization plans was developed with respect to five different number of unit-combination arrangement in order to have a total respective operational cost of the following: ₦8,176,503,40,800, ₦7,654,267,24,800, ₦7,499,530,60,800, ₦7,460,846,44,800 and ₦5,206,095,83,900. The research paper strongly identified the functional relationship between capacity and cost this shows that as capacity of the generating plant increases, the operational running cost of the power plant also increases this is being validated with two-tail test and spearman's rank correlation coefficient with (R_k : 0.99375) approximately +1 which shows that there is a correlation that exist between capacity and cost

Index Terms: optimization planning, generation expansion, cost-saving, decomposition techniques of electric power, profit.

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I INTRODUCTION

Considering the growing demand, increasing diversities of services, and advances in generation, transmission and distribution system which are prompting industries, companies, private-sector, individuals etc.[1]. to rapidly expand and modernize their networks in order to satisfy the consumer (the end-user in terms of energy demand [2].

The main function of a power generating station is to deliver power to the targeted number of consumers. However, the electric power demands of different consumers vary in accordance with their level of activities [3]. The result of this variation in demand is that the load on the power station is never constant; rather it varies from time to time[4].

Most of the complexities of modern power plan-operation gave rise from the inherent variability of the load demand by the users. Unfortunately, electrical power cannot be stored and the power station must produce power when demanded to meet the requirements of the consumer. Similarly, the power engineers would like the alternators in the power station to run at their rated capacity for maximizing efficiency, but the demands of consumers have wide variation. This makes the control of a power generating station highly complex to solve mathematically. Power stations control and operation are done, using engineering modeling, engineering optimization by decomposition technique etc [5].

Most of these models involve optimization approach or techniques. Ideally, without large scale storage, power supply and demand must be matched at all times, therefore, optimization of electric power generation for expansion planning and cost-solving can be solved in isolation from one period to the next in a consistent and continuous programme for different look-ahead periods. This paper presented a simple decomposition technique that would strongly put into consideration of the planning programme of the load forecast-result (for energy demand) with the aim of minimizing cost and maximizing profit (optimization-plan) [6].

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II BACKGROUND OF THE STUDY

Electric Power Generation Expansion Planning

Ideally, the power system planning and operation identified strongly the generation expansion planning (GEP), transmission expansion planning (TEP) and Distribution-Expansion Planning (DEP) respectively. This research work focuses mainly on generation expansion planning which is about engaging the current and the future states of a power system therefore; the information of the existing state of the system would seriously give an insight for proffering solution with good engineering decision. Evidently, this processesis aimed to decide on new plan (generation expansion) as well as upgrading existing system elements to adequately satisfy the loads requirements for the future expansion, the elements includes:

- Generation facilities
- Substations
- Transmission line/and or cables
- Capacitors/Reactors etc.

III MATERIALS AND METHOD

Decomposition Technique (Row-column matrix)
This is a mathematicaloperation of matrix multiplicationwhich occurs in engineering problem formulations as;

– If A is a row matrix that is : $\left[a_1,\ a_2,\ a_3\right] \Rightarrow$ row arrangment

Similarly,

- If B is a column matrixthat is :

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \Rightarrow \text{column arrangement}$$

– This evidently means that,

$$[A] = [a_1,\ a_2,\ a_3] \quad (1)$$

$$[B] = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad (2)$$

– In a similar manner, matrix [B] can also be rewritten as:

$$[B] = [b_1,\ b_2,\ b_3]^T \quad (3)$$

– By multiplication operation by matrices operations whichcan be decompose into matrices [AB] as:

$$[AB] = [a_1,\ a_2,\ a_3][b_1,\ b_2,\ b_3]^T \quad (4)$$

$$[AB] = \underbrace{[a_1,\ a_2,\ a_3]}_{\text{Capacity (MW)}} \overbrace{\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}}^{\text{Units}} \quad (5)$$

Hence, the decomposition by multiplication operation of matrix [AB] can be rewritten as:

$$[AB] = \sum_{i=1}^{n} A_i B_i = \begin{bmatrix} a_1 b_1 + a_2 b_2 + a_3 b_3 + \\ \dots\dots\dots\dots + a_n b_n \end{bmatrix} \quad (6)$$

– Sixteen (16) generating stations were captured in a developing country like Nigeria as a study case, while some stations are under proposed constructions for expansion processes. Specifically, forpurpose of this paper presentation three (3) generating stations were considered as case studies: Afam Power Station, Sapele power station and Egbin power generating station.

CAPACITY COMBINATION ANALYSIS

Analysis 1: Afam generating power station

- Theanalysis of thispaper rely on the installed capacity.
- Thermal power station
- Existing capacity = 980 MW
- Capacity addition due to the twenty years projection= 2250MW

Analysis2: First optimization plan
Capacity combination (MW)
(number of generation plant) Unit

$$\underset{\downarrow}{[200\quad 250\quad 300]}\quad \underset{\downarrow}{[1\quad 7\quad 1]^T}$$

The decomposition operation becomes:

$$[2250MW] = \underbrace{[200\quad 250\quad 300]}\begin{bmatrix} 1 \\ 7 \\ 1 \end{bmatrix}$$

$$= 200\times 1 + 250\times 7 + 300\times 1$$
$$= 200 + 1750 + 300$$
$$= \underline{\underline{2250MW}}$$

Analysis 3:Determination of the input-output curve of a generating unit from heat rate curve as:

$$F_i(PG_i) = PG_i\ H_i(PG_i) \quad (7)$$

The input-output of a generating unit specifies the input energy rate, $F_i(PG_i)$ in joule/hror cost of fuel used per hour that is $C_i(PG_i)$ in ₦/hr as a function of the generator power output (PG_i).

where:

$F_i(PG_i)$: The graph of input-output curve of input-energy rate.
$H_i(PG_i)$: The heat-rate in J/MWH or J/hr.
PG_i: The output power (MW)

Analysis 4: Determination of input-energy-rate $F_i(PG_i)$, if the heat-rate-curve function can be approximated in the form:

$$H_i(PG_i) = \frac{\alpha}{PG_i} + \beta + \gamma PG_i (J/MWH) \quad (8)$$

With the consideration and assumption that all the coefficient are positives.

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To establish and obtained the expression for input-energy rate, $F_i(PG_i)$ from equation (7) and (8) respectively as:

$$F_i(PG_i) = PG_i\ H_i(PG_i) \quad (9)$$

$$H_i(PG_i) = \frac{\alpha}{PG_i} + \beta + \gamma\, PG_i \quad (10)$$

Also, the fuel cost equation becomes:

$$C(PG_i) = F_i(PG_i) \quad (11)$$

Similarly,

$$Fi(PGi) = PGi\ Hi(PGi) \quad (12)$$

Now substitute $F_i(PG_i)$ into equation(11) to obtain as:

$$C(PG_i) = F_i(PG_i) = PG_i\ H_i(PG_i) \quad (13)$$

Therefore, substituting $H_i(PG_i)$ equation (10) into equation (7)to obtain as:

$$F_i(PG_i) = PG_i\left(\frac{\alpha}{PG_i} + \beta + \gamma\, PG_i\right) \quad (14)$$

$$F_i(PG_i) = \alpha + \beta PG_i + \gamma P^2 G_i\ (J/h) \quad (15)$$

Evidently, Equation (15) defined, the quadratic expression for input energy rate, $F_i(PG_i)$.

Analysis 5: Determination of fuel cost-equation, $C_i(PG_i)$

If the cost of fuel is ₦/Joule, then multiplying the fuel-input rate, $F_i(PG_i)$ by the cost of fuel per joule that is ₦/joule, to obtain the fuel cost as $C(PG_i)$.

Recall equation (15) as:

$$F(PG_i) = \alpha + \beta\, PG_i + \gamma\, PG_i^2 \quad (J/h) \quad (15)$$

Thus,

$$C(PG_i) = \alpha + \beta\, PG_i + \gamma\, PG_i^2\ (J/h) \times (₦/J) \quad (16)$$

or $C(PG_i) = \alpha + \beta\, PG_i + \gamma\, PG_i^2 \quad (₦/hr)$

Analysis 6: Cost Data Analysis of generating Capacity and fuel consumption pattern.

Determination of fuel-consumption coefficient (α, β, γ) from heat-rate equation $H(PG_i)$.

Analysis 7:Three (3) thermal generating stations were captured: Afam, Sapelle and Egbin power generating station for Analysis.

Analysis 8: Generating plantUnits capacity combination for the power stations includes: 200MW, 250MW and 300MW represented as; $(PG_1, PG_2\ and\ PG_3)$

Analysis 9: The heat-rate capacity of the generating plants are:

$$PG_1 = 200MW \quad (10J/MWH)$$
$$PG_2 = 250MW \quad (9J/MWH)$$
$$PG_3 = 300MW \quad (10J/MWH)$$

Analysis 10: Analysis for different loading, condition Generator (PG_1, PG_2, PG_3), percentage (%) capacity loading as: 25%, 40% and 100%.

Analysis 11: Capacity Combination Analysis for Afam generating power station:

The investigation and analysis rely on installed capacity.

Thermal power station
Existing capacity = 980MW
Capacity addition due to the twenty year projection = 2250MW.

Analysis 12: Expressing the heat-rate equation in terms of the threegenerators, $H(PG_1)$: $H(PG_2)$ and $H(PG_3)$, as:

$$H(PG_1) = \frac{\alpha_1}{PG_1} + \beta_1 + \gamma_1\, PG_1 \quad (17)$$

$$H(PG_2) = \frac{\alpha_2}{PG_2} + \beta_2 + \gamma_2\, PG_2 \quad (18)$$

$$H(PG_3) = \frac{\alpha_3}{PG_3} + \beta_3 + \gamma_3\, PG_3 \quad (19)$$

where,:

$$H(PG_1) = 10J/MWH$$
$$H(PG_2) = 9J/MWH$$
$$H(PG_3) = 10J/MWH$$
$$PG_1(25\%\ loading) = 562.5MW$$
$$PG_2(40\%\ loading) = 562.5MW$$
$$PG_3(100\%\ loading) = 2250MW$$

Analysis 13: Substituting the data into equation (17, 18 and 19) respectively:
This implies:

$$10J/MWH = \frac{\alpha_1}{563} + \beta_1 + \gamma_1 \times 563 \quad (20)$$

$$9J/MWH = \frac{\alpha_2}{900} + \beta_2 + \gamma_2 \times 900 \quad (21)$$

$$10J/MWH = \frac{\alpha_3}{2250} + \beta_3 + \gamma_3 \times 2250 \quad (22)$$

Arranging the algebraic equations together as:

$$10 = 0.001776\alpha_1 + \beta_1 + 563\gamma_1 \quad (23)$$
$$9 = 0.00111\alpha_2 + \beta_2 + 900\gamma_2 \quad (24)$$
$$10 = 0.00444\alpha_3 + \beta_3 + 2250\gamma_3 \quad (25)$$

Analysis 14: - Recall the fuel–consumption coefficient (fuel – cost parameters) using determinant by matrix technique as:

α, β,γ as :
α = 2506.69
β = 4.418
γ = 0.00184

Analysis 15: The capacity analysis for Afam power generating station in Nigeria as:

$$[PG_1, PG_2, PG_3] = [200\ 250\ 300]\begin{bmatrix}1\\7\\1\end{bmatrix}$$

$$= 200\times1 + 250\times7 + 300\times1$$

Analysis 16: Implementing the optimization techniquesfor expansion planning and cost-saving as:

$$C_i(PG_i) = \alpha + \beta PGi + \gamma PG_i^2 \quad (\$/hour\ or\ ₦/h) \quad (17)$$

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Analysis 17: Substitute the variables, $PG_1, \alpha, \beta, \gamma$ into the cost function equation (16)as:

$$PG_1 = 200 \times 1 = 200MW \quad or$$

$$PG_1 = 200MW$$

Thus,

$$C_1(200MW) = 2506.69 + 4.418 \times 200 + 0.00184 \times (200)^2 \ or$$

$$C_1(200MW) = 2506.69 + 883.6 + 73.6$$

$$C_1(200MW) = 3{,}463.89 \ \$/hour$$

$$C_1(200MW) = 692{,}778 \ ₦/hour$$

Similarly, for capacity of generator (PG_2), given as;

PG_2 = 250 × 7 = 1759MW or

PG_2 = 1750MW, α = 2506.60,
β = 4.418, γ= 0.00184

This implies,

$$C_2(1750MW) = 2506.69 + 4.418 \times 1750 + 0.00184 \times (1750)^2$$

$$= 2506.69 + 7731.5 + 5635$$

$$C_2(1750MW) = 15{,}873.19 \ S/hour$$

$$C_2(1750MW) = 3{,}174{,}638 ₦/hour$$

Similarly, we can solve for PG_3 as:

PG_3 = 300 × 1 = 300MW

Hence,

PG_2 =300MW, α = 2506.60,
β = 4.418, γ= 0.00184

Evidently,

$$C_3(300MW) = 2506.69 + 4.418 \times 300 + 0.00184 \times (300)^2 \ or$$

= 2506.69 + 1325.4 + 165,6or

$$C_3(300MW) = 3{,}997.69 (\$/hour)$$

$$C_3(300MW) = 799{,}538 \ ₦/hour$$

Analysis 18: Determination of total cost (n) of the optimization plan–1 for the capacity combination strategy analysis given as:

$$n_1 = C_{T1} = C(200MW)_1 + C(1750)_2 + C_3(300MW)$$

$$= 4{,}666{,}954 ₦/hour$$

For 20 year - projection hours = 20 x 8760 hours = 175,200 hours

Therefore, $n_1 = 4{,}666{,}954 \ ₦/hour \times 175{,}200$

$$n_1 = ₦817650340800$$

Repeat the same process for n_1, n_2, n_3, n_4 and n_5 respectively.

IV RESULTS AND DISCUSSION

n_1 (*plan* 1) = *Total* cos*t* = ₦817650340800

n_2 (*plan* 2) = *Total* cos*t* = ₦765426724800

n_3 (*plan* 3) = *Total* cos*t* = ₦749953060800

n_4 (*plan* 4) = *Total* cos*t* = ₦746084644800

n_5 (*plan* 5) = *Total* cos*t* = ₦520609583900

Since, $n_1 > n_2 > n_3 > n_4 > n_5$, then,

$n_1 - n_2$ = ₦5222361600

$n_2 - n_3$ = ₦154736640000

$n_3 - n_4$ = N3,868,416,000

$n_4 - n_5$ = ₦225475060900

$$n_1 - n_5 = (n_1 - n_2) + (n_2 - n_3) + (n_3 - n_4) + (n_4 - n_5)$$

or

$n_1 - n_5$ = ₦297040756900

Analysis 19:

$$(\% \ saving) = \frac{n_1 - n_2}{n_1 - n_5} \times 100\%$$

$$= \frac{52223616000}{297040756900} \times 100\%$$

$$= 17.58129643\% \approx 17.58\%$$

Analysis 20:

$$(\% \ saving) = \frac{n_2 - n_3}{n_1 - n_5} . \times 100\%$$

$$= \frac{15473664000}{297040756900} \times 100\%$$

$$= 5.209273017\% \approx 5.21\%$$

Analysis 21:

$$(\% \ saving) = \frac{n_3 - n_4}{n_1 - n_5} . \times 100\%$$

$$= \frac{3868416000}{297040756900} \times 100\%$$

$$= 1.302318254\% \approx 1.30\%$$

Analysis 22:

$$(\% \ saving) = \frac{n_4 - n_5}{n_1 - n_5} . \times 100\%$$

$$= \frac{225475060900}{297040756900} \times 100\%$$

$$= 75.90711229\% \approx 75.91\%$$

Analysis 23:

$$Total \ saving \ (n_1 - n_5) = ₦52223616000 + 15473664000 + ₦3868416000 + ₦225475060900$$

$$= N2970407569000$$

Check (percentage saving):

$$17.58\% + 5.21\% + 1.30\% + 75.91\% = 100\%$$

Table 1: Cost of optimal expansion plans for twenty-year look-ahead periods with optimization strategy (with plans($n_1 - n_5$)

Different optimization plans (n)	Capacity combination (MW)			No. of units			Total cost (₦) (n), C_T=n = C_1+C_2+C_3 (₦)
	(MW) pg_1	(MW) pg_2	(MW) pg_3				
n_1 = plan 1	200 MW	250 MW	300 MW	U_1 =1	U_2 = 7	U_3 =1	₦817,650,340,800
n_2 = plan 2	200 MW	250 MW	300 MW	U_1 =7	U_2 = 1	U_3 =2	₦765,426,724,800
n_3 = plan 3	200 MW	250 MW	300 MW	U_1 =4	U_2 = 1	U_3 =4	₦749,953,060,800
n_4 = plan 4	200 MW	250 MW	300 MW	U_1 =2	U_2 = 5	U_3 =2	₦746,084,644,800
N_5 = plan 5	200 MW	250 MW	300 MW	U_1 =3	U_2 = 3	U_3 =3	₦520,609,583,900

Table 2: Capacity and Cost Ranking Processes

S/No	Ranked (MW) according to capacity	Rank (R_1) capacity	Ranked according to cost (₦)	Ranked (R_2) R-Cost	$d=R_1-R_2$	d^2
1.	$U_1 = 1\times200= 200$	1	692,778	1.5	–0.5	+0.25
	$U_2 = 7\times250= 1750$	15	3,174,638	15.5	–0.5	+0.25
	$U_3 = 1\times300= 300$	3	799,538	3.5	–0.5	+0.25
2.	$U_1 = 7\times200= 1400$	11.5	2,459,658	11	+0.5	+0.25
	$U_2 = 1\times250= 250$	2	745,238	2.5	–0.5	+0.25
	$U_3 = 2\times300= 600$	5	1,163,978	4.5	+0.5	+0.25
3.	$U_1 = 4\times200= 800$	7	1,443,738	7.5	–0.5	+0.25
	$U_2 = 1\times250= 250$	2	745,238	2.5	–0.5	+0.25
	$U_3 = 4\times300= 1200$	9.5	2,091,578	9.0	+0.5	+0.25
4.	$U_1 = 2\times200= 400$	4.5	913,658	4.0	+0.5	+0.25
	$U_2 = 5\times250= 1250$	11	2,180,838	11.5	–0.5	+0.25
	$U_3 = 2\times300= 600$	5	1,163,978	4.5	+0.5	+0.25
5.	$U_1 = 3\times200=600$	5	1,163,978	4.5	+0.5	+0.25
	$U_2 = 3\times250= 750$	6.5	1,371,038	6.0	+0.5	+0.25
	$U_3 = 3\times300= 900$	8.5	1,594,658	8.5	0	0
		$\Sigma R_1 = 96.5$		$\Sigma R_2 = 96.5$	$\Sigma d = 0$	$\Sigma d^2 = 3.5$

Using spearman correlation coefficient relationship as:

$$r_k = 1 - \frac{6\Sigma d^2}{n^2 - n} = 1\frac{6\Sigma d^2}{n(n^2-1)}$$

Substitute the numerical values into the equation(26)as:

$$r_k = 1 - \frac{6\Sigma d_i^{\,2}}{n(n^2-n)}$$

$$r_k = 1 - \frac{6\times3.5}{15(15^2-1)}$$

$$r_k = 1 - \frac{21}{15(225-1)}$$

$$r_k = 1 - \frac{21}{15\times224} = 1 - \frac{21}{3360}$$

$$r_k = 1 - \frac{21}{3360}$$

$$r_k = 1 - 0.00625$$

$$r_k = 0.99375$$

$$r_k \approx +1$$

V. CONCLUSION AND RECOMMENDATION

This paper presented an optimization of electric power generation for expansion planning and cost saving, using decomposition techniques. The techniques is highly flexible and proffer fast solution to problems and developed five optimization plans, in terms of mix-capacity combination for the selection of some generating station in Nigeria in order to search for the best capacity combination with respect to cost, thereby to derive financial benefits and cost-serving. This paper presented and formulated a decomposition techniques, which is used to analyse the breaking down processes of capacity combination in order to provide for an optimization search, with the aim of derive financial objectives through cost-function implementations. This paper strongly rely on the analysis of load forecast results on the view to know the capacity of energy generation to be produced at different generating station, particularly in Nigeria.

Optimization of electric power generation for expansion planning and cost saving hold significant role in the future activities of every given nations, for purpose of regular power supply for effective and efficient micro and macro economic activities.

Therefore it is strongly recommended that generating capacity of a given generating station, must regularly be check for purpose of matching capacity generation and energy demand equilibrium at the receiving –end (consumers). That is mismatches as a result of violation, contingencies etc between generation of power and energy demand scenario may seriously led to system collapse. Hence, integration of mixed capacity combination set of generating unit will provide optimal options for cost saving; for purpose of deriving financial benefits.

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