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OPTIMIZATION OF ELECTRIC POWER GENERATION FOR EXPANSION PLANNING AND COST-SAVING, USING DECOMPOSITION TECHNIQUES

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ABSTRACT: This paper formulated the framework of optimization of electric power generation for expansion planning and cost saving. The inability of the Nigeria power system to generate enough electric power, has led to extra-ordinary power losses on the line due to the over load problems, thereby making the power system planning, and running cost outrageous. The research technique considered the application of decomposition method for an optimization search in a way 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 capacity allocation to the generating stations in Nigeria, which include some of the following:2250MW capacity to Afam, 2350MW capacity to Sapele and 3000MW capacity to Egbin power generating station as expected power to be generated from these station). The paper examined the existing capacity of the generating stations, and considered the 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 in order to have different options for the best selection. The row and column capacity arrangement are implemented into the decomposition equation, in way to break-down the capacity – allocation into different unit-combination, which evidently substituted into the cost equations to derived financial objective, to make a savings. Five optimization plans was developed with respect to five different number of unit-combination arrangement in order to have a total operational cost with: N8,176,503,40,800, N7,654,267,24,800, N7,499,530,60,800, N7,460,846,44,800 and N5,206,095,83,900. The research strongly identified the functional relationship between capacity and cost that is, as capacity of the generating plant increases, the cost of running the power plant also increases, this is 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, according to spearman's rank correlation coefficient +1 indicates complete agreement, –1 indicates complete disagreement, while 0 indicates no association or relation between the two set of variables. Therefore, the paper identified strongly the synergy between capacity (MW) and cost (N), which is strong term determine the level of saving while searching from generator mix capacity (into different number of unit-combination arrangement, in a way to satisfy the financial obligation, thereby minimizing the cost arrangement and maximizing profit, in order the achieve an effective generation expansion planning at all time making the system the power system to run at satisfactory condition.

Keywords: capacity mix-combination, cost-saving, decomposition techniques, generation expansion, load energy-demand, optimization of electric power, planning, generating.

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1. 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. to rapidly expand and modernize their networks in order to satisfy the consumer (the end-user in terms of energy demand [3].

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 [4]. 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.

"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 work presents 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].

2. 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, it is all about thinking of the current and the future states of a power system; this information of the existing state of the system would seriously give an insight for proffering solution with good engineering decision. In other words, it is a process in which the aim is to decide on new plan (generation expansion) as well as upgrading existing system elements, to adequately satisfy the loads for a foreseen future; the elements may be:

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

3. Decomposition Technique (Row-column matrix)

This is a operation case of matrix multiplication, which occurs in engineering problem formulations

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

Similarly,

If B is a column matrix, that is: $\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \Rightarrow$ 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, by matrices operations, we can decompose 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 of matrix [AB] can be rewritten as:

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

– For the purpose of this research work, sixteen (16) generating station were captured in Nigeria, while some stations are under proposed construction process. Specifically, three (3) generating stations were considered as case studies: Afam Power generating Station, Sapele power generating station and Egbin power generating station.

4. Capacity Combination Analysis

Case Study 1: Afam generating power station

- The research work rely on installed capacity.
- Thermal power station
- Existing capacity = 980 MW
- Capacity addition due to the twenty years projection= 2250MW

Case 1: First optimization plan

Capacity combination (MW) Unit (number of generation plant)

$$\downarrow$$

$$[200 \quad 250 \quad 300]$$

$$\downarrow$$

$$[1 \quad 7 \quad 1]^T$$

Then, by the operation of decomposition:

$$[2250MW] = \underbrace{[200 \quad 250 \quad 300]}_{\text{Capacity (MW)}} \begin{bmatrix} 1 \\ 7 \\ 1 \end{bmatrix}$$

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

Analysis 1:

Determine the input-output curve of a generating unit from heat rate curve.

$$F_i(PG_i) = PG_i \; H_i(PG_i) \qquad (7)$$

The input-output of a generating unit specifies the input energy rate, $F_i(PG_i)$ in joule/hr or 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 2: Determination of input-energy-rate $F_i(PG_i)$, if the heat-rate-curve function can be approximated in the form:

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

With the assumption that, all the coefficient are positives.

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

$$F_i(PG_i) = PG_i \, H_i(PG_i) \qquad (9)$$

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

Also, the fuel cost equation becomes;

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

Also,

$$Fi(PGi) = PGi \; Hi(PGi) \qquad (12)$$

Now substitute $F_i(PG_i)$ into equation 11 we have as:

Also, $C(PG_i) = F_i(PG_i) = PG_i \, H_i(PG_i)$ (13)

Therefore, substituting $H_i(PG_i)$ in equation 10 into equation 7 we have as:

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

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

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

Analysis 3: 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, we obtained the fuel cost $C(PG_i)$.:

Recalled equation (15):

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

Then,

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

or

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

4. Cost Data Analysis/Capacity, fuel consumption data

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

Case 1

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

Case 2

Units capacity combination for the generating station are: 200MW, 250MW and 300MW $(PG_1, PG_2 \; and \; PG_3)$

Case 3

The heat-rate capacity of the generators are:

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

Case 4

Analysis for different loading, condition

Generator $(PG_1, \; PG_2, PG_3)$, percentage (%) capacity loading as: 25%, 40% and 100%.

Case 5

Capacity Combination Analysis for "Afam generating power station":

The research work rely on installed capacity.

Thermal power station

Existing capacity = 980MW

Capacity addition due to the twenty year projection = 2250MW.

Case 6

Expressing the heat-rate equation in terms of three(3) generators, $H(PG_1)$: $H(PG_2)$ 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:

$$H(PG_1) = 10J/MWH$$

$$H(PG_2) = 9J/MWH$$

$$H(PG_3) = 10J/MWH$$

$$PG_1(25\% \ loading) = 562.5MW$$

$$PG_2(40\% \ loading) = 562.5MW$$

$$PG_3(100\% \ loading) = 2250MW$$

Case 7

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 them together, we have:

$$10 = 0.001776\alpha_1 + \beta_1 + 563\gamma_1 \quad (23)$$

$$9 = 0.00111\alpha_2 + \beta_2 + 900\gamma_2 \quad (24)$$

$$10 = 0.00444\alpha_3 + \beta_3 + 2250\gamma_3 \quad (25)$$

Case 1 - A

Recalling the fuel – consumption coefficient (fuel – cost – parameters) determined using determinant by matrix:

α, β,γ as :

α = 2506.69

β = 4.418

γ = 0.00184

Activity 1

Recalling the capacity analysis for Afam power generating station in Nigeria:

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

$$= 200 \times 1 + 250 \times 7 + 300 \times 1$$

Activity 2

Implementing the analysis of optimization – research for expansion planning and cost-saving as:

$$C_i(PG_i) = \alpha + \beta PGi + \gamma PG_i^2 \quad (17)$$

$$(\$/hour \ or \ ₦/h)$$

Activity 3

Substitute the variable, element, PG_1, α, β, γ into the cost function equation (16), this

Means that;

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

$$PG_1 = 200MW$$

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), we have:

$$PG_2 = 250 \times 7 = 1750MW \quad or$$

$$PG_2 = 1750MW, \ \alpha = 2506.69, \beta = 4.418, \ \gamma = 0.00184$$

This implies,

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

$$= 2506.69 + 7731.5 + 5635$$

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

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

In the same manner, we can solve for PG_3 as:

$$PG_3 = 300 \times 1 = 300MW \quad or$$

Hence,

$$PG_3 = 300MW, \alpha = 2506.69, \ \beta = 4.418, \gamma = 0.00184$$

Evidently,

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

$$= 2506.69 + 1325.4 + 165.6 \quad or$$

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

$$C_3(300MW) = 799{,}538 \ ₦/hour$$

Activity 4

Determination of total cost (n) of the optimization – "plan – 1" for the capacity combination strategy:

This implies,

$$n_1 = C_{T1} = C(200\,MW)_1 + C(1750)_2 + C_3(300MW)$$
$$= 4{,}666{,}954 ₦/hour$$

For 20 year - projection hour = 20 x 8760 hours

$= 175{,}200$ hours

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

$$n_1 = ₦817650340800$$

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

5. Presentation of five optimization plan for twenty year (20yrs) projection:

$n_1(plan\,1) = Total\ cost = ₦817650340800$

$n_2(plan\,2) = Total\ cost = ₦765426724800$

$n_3(plan\,3) = Total\ cost = ₦749953060800$

$n_4(plan\,4) = Total\ cost = ₦746084644800$

$n_5(plan\,5) = Total\ cost = ₦520609583900$

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

$n_1 - n_2 = ₦5222361600$

$n_2 - n_3 = ₦154736640000$

$n_3 - n_4 = ₦3{,}868{,}416{,}000$

$n_4 - n_5 = ₦225475060900$

$$n_1 - n_5 = (n_1 - n_2) + (n_2 - n_3) + (n_3 - n_4) + (n_4 - n_5) \quad or$$

$$n_1 - n_5 = ₦297040756900$$

Case 6 – F

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

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

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

Case 7 – G

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

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

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

Case 8 – H

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

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

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

Case 9 – I

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

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

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

Case 10 – J

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

$$= N\,2970407569000$$

Check (percentage saving):

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

Table 3.1: Cost of optimal expansion plans for twenty-year look-ahead periods with optimization, plant (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 4.6: Capacity cost ranking

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 = 1×200= 200	1	692,778	1.5	–0.5	+0.25
	U_2 = 7×250= 1750	15	3,174,638	15.5	–0.5	+0.25
	U_3 = 1×300= 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:

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

Substituting the tabular values into the equation 4.1 as:

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

$$r_k = 1 - \frac{6\times 3.5}{15(15^2 - 1)}$$

or

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

or

$$r_k = 1 - \frac{21}{15\times 224} = 1 - \frac{21}{3360}$$

or

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

or

$$r_k = 1 - 0.00625$$

or

$$r_k = 0.99375$$

or

$$r_k = +1$$

Conclusion

This study presents an optimization of electric power generation for expansion planning and cost saving, using decomposition techniques. The techniques is highly flexible, 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; thereby searching for the best capacity combination with respect to cost, in order to derive financial benefits and cost-serving. This study presents and formulates 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 deriving financial objectives through cost-function implementations. The works strongly rely on the conduction of load forecast results in order to know the capacity of energy generation to be produced at different generating station, particularly in Nigeria.

References

[1] Ault, G.W. & Donald, J. R. Mc, (2000). Planning for distributed generation within distributed networks in restructured electricity markets, *IEEE Power Eng. Reveiwed*, 30(20), 52-54.

[2] Energy Commission of Nigeria (ECN) (2003). National energy policy. Federal Republic of Nigeria, Abuja.

[3] Adenikinju, A (2005). Analysis of the cost of infrastructure failures in a developing economy the case of electricity sector in Nigeria. *African Economic Research Consortium (AERC) Research Paper*, 1489, Nairobi. February 2005.

[4] Akinbami, J.F.K. (2001). Renewable Energy Resources and technologies in Nigeria: present situation, future prospects and policy framework. mitigation and adaptation strategies for global change. Netherlands: Kluwer Academic Publisher.

[5] Amotsuka, P.O. (2008). Sustainable agriculture in the Niger Delta Region: A case study of Fatima Community of Rivers State. A paper Presented at 2nd National Conference of Colleges of Agriculture, Environmental, Engineering and Science

and Technology, Hassan Usman Katsina Polytechnic.

[6] Babalola, R. (2009, November 6). 6000MW Power target report card. *Daily Trust Newspaper,* 22, 94.

[7] Haffner, S., Alver Pereira, L.F., Perira, L.A., & Barreto, L. S., (2008). Multistage model for distribution expansion planning with distributed generation – Part 1: Problem formulation, *IEEE Transaction Power System.*, 23(5), 915-923.

[8] Ibitoye F, & Adenikinju A (2007). Future demand for electricity in Nigeria. Applied energy 84(24), 100-116.

[9] Ilic, M., Galiana, F., & Fink L, (1998). Power system restructuring system Economics, Kiluwei Academic Publishers.

[10] Jeremy A. Bloom (2002). Solving an electricity capacity expansion planning problem by Generalized Benders' decomposition.

[11] Ojinaka , I.J. (2008). *Energy crisis in Nigeria, The role of natural gas*, *The Bullion,* The publication of Central Bank of Nigeria, 22 (4), 78-97.

[12] Sambo, A.S. (2008) Matching electricity supply with demand in Nigeria. International association of energy economics, 4(3),32-36.

[13] Wadwa, C. L. (2011). Generation distribution and utilization of electrical energy. A new