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Optimization of an Expanded Nigeria Electricity Grid System using Economic Load Dispatch

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Abstract: *The objective of an economical and reliable power system is to ensure that customer's load requirements are met at a reduced cost of generation. Economic Load Dispatch (ELD) determines the power output of each thermal power plant, which minimizes the overall cost of fuel needed to serve the entire system load. This study carried out an optimization analysis on the economical distribution of loads on the existing and expanded thermal plants. The optimization analysis was carried out by formulating ELD problem using MATLAB software packages. This was with a view of developing a dynamic load scheduling between the aforementioned, in order to reduce cost, enhance overall performance and reliability of the system. The obtained result shows it is efficient and cost-effective to operate and generate power in the expanded grid. Correspondingly, the expansion of the grid to include new thermal plants of Olorunsogo, Omotoso and Geregu eased the load stress on the old plants of Afam, Egbin, Sapele and Ughelli: thereby mitigating the effect of power transmission loss and offsetting the total cost of generation.*

Keywords: Cost Analysis, Economic Load Dispatch, Load Demand, Optimization and Transmission Loss

1. INTRODUCTION

The modern power system around the world has grown in complexity of interconnection and power demand. The focus has shifted towards enhanced performance, increased customer focus, low cost, reliable and clean power [1]. The Economic Load Dispatch involves allotting generation levels to the various generating plants in a power system network in order to ensure optimal and economical supply to the system load [2].

In order to maintain a high degree of economy and reliability of the power system, economic dispatch is one of the options available to the utility companies. Economic dispatch allocates the total power demand among the online generating units in order to minimize the cost of generation while satisfying pertinent system constraints [3]. Economic Load Dispatch (ELD) problem play a vital role in the operation of power system it is the short-term determination of the optimal output of the number of electricity generation facilities, to meet the system load, at the lowest possible cost subjected to transmission and operational constraints. [4]

Economic Load Dispatch (ELD) is a sub problem of the optimal power flow (OPF) having the objective of fuel cost minimization. The fuel cost equation of a thermal plant is generally expressed as continuous quadratic equation. In real situations, the fuel cost equations can be discontinuous [5]. Owing to the increasing complexity of interconnections, the size of the areas of electric power systems, scarcity of energy resources, increasing power generation cost and environmental concern, it is necessary to minimize the expenses through optimal economic dispatch. For the total cost of generation and transmission to be minimum at a forecasted load demand, Economic Dispatch defines the production level of each participating generating plant.

In Nigeria like other countries, power stations are far from the loads at diverse distances. Consequently, these generating stations have dissimilar fuel cost functions. Hence for providing cheaper power, load has to be distributed among various power stations in a way which results in lowest cost for generation.

Whether a generator should participate in sharing the load at a given interval of time is a problem of unit commitment. Once the unit commitment problem has been solved, it becomes a problem of optimal allocation of the available generations to meet the forecasted load demand for the current interval [6]

In a practical power system, the power plants are not located at the same distance from the centre of loads and their fuel costs are different. Also, under ideal operating conditions, the generation capacity is more than the total load demand and losses. Thus, there are many options for scheduling generation. In an interconnected power system, the objective is to find the real and reactive power scheduling of each power plant in such a way as to minimize the operating cost. This means that the generators' real power and reactive power are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost. [7]. The objective of economic load dispatch is to minimise the overall cost of generation

For the purpose of economic dispatch studies, online generators are represented by functions that relate their production cost to their power output. Quadratic cost functions are used to model generator in order to simplify the mathematical formulation of the problem and to allow many of the conventional optimization techniques to be used. The economic dispatch problem is traditionally solved using conventional mathematical techniques such as lambda iteration and gradient schemes. These approaches require that fuel cost curves should increase monotonically to obtain the global optimal solution. The input-output of units are inherently non-linear with valve point loading or ramp rate limits and having multiple local minimum points in the cost function [8].

2. PROBLEM FORMULATION

The objective of economic dispatch problem is to operate our power system in a manner that minimizes the costs of generator. In other words, Economic dispatch determines the best way to minimize the current generator operating costs.

It assumes that there are N units already connected to the system. The purpose of the economic dispatch problem is to find the optimum policy for these N units. The lambda-iteration method is a good approach for solving the economic dispatch problem: generator limits are easily handled, penalty factors are used to consider the impact of losses. Economic dispatch is not concerned with determining which units to turn on/off. Basic form of economic dispatch ignores the transmission system limitations

In this system, the essential condition is to balance the sum of the generated powers P_i and the load demand P_D [9] and [10]

$$\sum_{i=1}^{n_g} P_i = P_D \qquad (1)$$

Electrical power systems are designed and operated to meet the continuous variation of power demand. In power system minimizing, the operation cost is very important [2]

Assume that C_t is equal to the total cost for supplying the indicated load. The problem is to minimize C_t subject to the constraints that are the sum of the power generated in each unit as in equation (1). In this solution process, operating limits of each generation unit must be known. That is,

$$C_t = \sum_{i=1}^{n_g} C_i = \sum_{i=1}^{n_g} \alpha_i + \beta_i P_i + \gamma_i P_i^2 \qquad (2)$$

C_i is the cost rate of the unit. The output of each unit is P_i, which represents the electrical power output of units. Where α_i, β_i and γ_i are the coefficients of the quadratic cost function of the unit's power.

When transmission distances are very small and load density is very high, transmission losses may be neglected and the optimal dispatch of generation is achieved with all plants operating at equal incremental production cost. However, in a large interconnected network where power is transmitted over long distances with low load density areas, transmission losses are major factor and affect the optimum dispatch of generation. The losses on the transmission system are a function of the generation dispatch

Losses can be included in the optimization formulation by slightly rewriting the Lagrangian:

$$\mathrm{L} = C_t + \lambda(P_D + \mathrm{P}_L - \sum_{i=1}^{n_g} P_i) + \sum_{i=1}^{n_g} \mu_{i(\max)}(P_i - P_{i(\max)}) + \sum_{i=1}^{n_g} \mu_{i(\min)}(P_i - P_{i(\min)}) \qquad (3)$$

Where L is the Lagrangian function of the power generated (P_i) and lambda (λ), $P_{i(\min)}$ and $P_{i(\max)}$ are the minimum and maximum generating limits respectively for a given plant I and P_L is the power loss

The minimization of the cost function in the equation (3) is subject to several restrictions capturing both the power and heat balance of the system, and the operational constraints of the generator [11].

The necessary condition for an optimal economic dispatch shown in equation (4) is obtained by differentiating equation (3) with respect to P_i.

$$\frac{\partial L}{\partial P_i} = \frac{\partial C_t}{\partial P_i} + \lambda(0 + \frac{\partial P_L}{\partial P_i} - 1) = 0 \qquad (4)$$

Equality constraint imposed by the losses and load demand.

$$P_D + P_L - \sum_{i=1}^{n_g} P_i = 0 \qquad (5)$$

Solving equation (4) for λ we get

$$\frac{dC_i}{dP_i} - \lambda(1 - \frac{\partial P_L}{\partial P_i}) = 0 \qquad (6)$$

$$\lambda = \frac{1}{\left(1 - \frac{\partial P_L}{\partial P_i}\right)} \frac{dC_i}{dP_i}$$

Where the penalty factor L_i is defined by

$$\mathrm{L_i} = \frac{1}{\left(1 - \frac{\partial P_L}{\partial P_i}\right)} \qquad (7)$$

Thus the effect of transmission losses is to introduce a penalty factor with a value that depends on the location of the plant with respect to the loads. In the equation for lambda (λ) as shown in equation (6) it is clear that the most economic cost of dispatch is obtained when the incremental cost multiplied by the corresponding penalty factor are equal for all the participating plants. Hence, $L_i > 1$; more expensive and $L_i < 1$; less expensive

The incremental transmission loss can be found from the loss equation and is given by

$$\frac{\partial P_L}{\partial P_i} = 2\sum_{j=1}^{n_g} B_{ij} P_j + B_{0i} \tag{8}$$

And the incremental production cost is given by

$$\frac{dC_i}{dP_i} = 2\gamma_i P_i + \beta_i \tag{9}$$

Substituting equations (8) and (9) into

$$\frac{\partial C_i}{\partial P_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda \tag{10}$$

We have equation (11)

$$\beta_i + 2\gamma_i P_i + 2\lambda \sum_{j=1}^{n_g} B_{ij} P_j + B_{0i}\lambda = \lambda \tag{11}$$

Dividing through by 2λ and pulling out B_{ii} from the summation, we have equation (12)

$$\left(\frac{\gamma_i}{\lambda} + B_{ii}\right) P_i + \sum_{j=1, j\neq i}^{n_g} B_{ij} P_j = \frac{1}{2}\left(1 - B_{0i} - \frac{\beta_i}{\lambda}\right) \tag{12}$$

This can be extended for all the plants in linear equations in matrix form to have

$$\begin{bmatrix} \frac{\gamma_1}{\lambda} + B_{11} & B_{12} & \cdots & B_{1ng} \\ B_{21} & \frac{\gamma_2}{\lambda} + B_{22} & \cdots & B_{2ng} \\ \vdots & \vdots & \ddots & \vdots \\ B_{ng1} & B_{ng2} & \cdots & \frac{\gamma_{ng}}{\lambda} + B_{ngng} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{ng} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 - B_{01} - \frac{\beta_1}{\lambda} \\ 1 - B_{02} - \frac{\beta_2}{\lambda} \\ \vdots \\ 1 - B_{0ng} - \frac{\beta_{ng}}{\lambda} \end{bmatrix}$$

$$[E][P] = [D] \tag{13}$$

To find the optimal dispatch first an estimated guess of λ, say $\lambda^{(1)}$ is made. Thus, from equation (13) we have P_i at the kth iteration expressed as

$$P_i^{(k)} = \frac{\lambda^{(k)} - \beta_i}{2\left(\gamma_i + \lambda^{(k)} B_{ii}\right)} \tag{14}$$

Applying the equality constraint in equation (5), expanding with Taylor's series about operating point $\lambda^{(k)}$, and neglecting the higher order terms results in

$$\Delta\lambda^{(k)} = \frac{\Delta P^{(k)}}{\sum \left(\frac{dP_i}{d\lambda}\right)^{(k)}} \tag{15}$$

And therefore,

$$\lambda^{(k+1)} = \lambda^{(k)} + \Delta\lambda^{(k)} \tag{16}$$

Where

$$\Delta P^{(k)} = P_D + P_L^{(k)} - \sum_{i=1}^{n_g} P_i^{(k)} \tag{17}$$

3. RESULTS AND DISCUSSION

The thermal plant generation limits used as input for this optimization analysis are shown in the Table 1. Hence indicating the freedom of operation of the thermal plants.

Table 1: Thermal plant generation limits

Plants	P_i (min) in MW	P_i (max) in MW
Omotoso	60	335
Olorunsogo	60	335
Geregu	80	414
Afam	150	977
Egbin	220	1300
Sapele	190	1020
Ugheli	145	972

The economic load dispatch results of the thermal generating stations of Afam, Egbin, Sapele and Ugheli which constitute the old grid is shown in the Table 2. Table 2 presents how the four thermal plants handle the total power demands between 705 MW 3873 MW.

The total generation cost increases with the increase in overall generation as shown in the figure 1. As the total power demands tends toward 3873 MW, the cost of generation increases exponentially as a result of the operation of most of the thermal plants around their maximum limit. This operation around limit does not only affect the total fuel cost, it also affects the power transmission loss. As total transmission loss is a function of power generated, the power losses in transmission are also taken care of by the generating plants. Hence the increase in transmission loss as a result of operating plants around their limit also increases the total cost of fuel. The optimization program started operating Egbin around its limit of 1300 MW in order to meet the total demand of 1893 MW at total generation cost of 178694.78 $/h.

The operation of Egbin at the maximum limit continued even after increasing the total power demand to 2685 MW but now, Afam is also operated at the limit. Subsequently, Sapele joined in the operation around limit when the total demand was increased further. The implication of this is that it's most efficient to bring these thermal plants into their maximum operation in the following order; Egbin, Afam, Sapele and lastly Ugheli in the quest to increase the total demand as presented in Table 2

Table 2: Old Thermal Plants Economic Load Dispatch

Plants	705 MW	1101 MW	1497 MW	1893 MW	2289 MW	2685 MW	3081 MW	3477 MW	3873 MW
Afam	150.00	150.00	250.40	419.00	676.90	977.00	977.00	977.00	977.00
Egbin	246.88	682.93	969.48	1215.30	1300.00	1300.00	1300.00	1300.00	1300.00
Sapele	190.00	225.60	340.08	457.50	641.70	914.90	1020.00	1020.00	1020.00
Ugheli	145.00	145.00	145.00	145.00	145.00	145.00	533.90	972.00	972.00
Cost ($/h)	68357.14	88840.9	125909.42	178694.78	254626.36	374522.45	716255.08	1505219.65	7101304.26

Similarly, the economic load dispatch result of expanded grid to include the old thermal generating plants of Afam, Egbin, Sapele and Ugheli and new plants of Omotoso, Olorunsogo and Geregu is presented in Table 3.

Evidently, the total generation cost of the expanded grid increases with the increase in overall generation as shown in the figure 1. All through the increase in the generation, the cost of generation increases linearly even with the operation of the thermal plants around their maximum limit. The optimization program started operating the new thermal plants of Omotoso, Olorunsogo and Geregu around their limit even at lower power total demands at a minimum total generation cost of 117485.66 $/h.

This operation of new thermal plants at the maximum limit continued all through the generation increase from 1101 MW to 4665 MW. Consequently, as the load demand increases the old thermal plants are brought gradually into maximum operation.

The optimization results imply that it is more efficient to bring these new thermal plants into their maximum operation in order to meet the increasing load demand. Subsequently, the older thermal plants are brought into their maximum operation in this order; Egbin, Afam, Sapele and lastly Ugheli. This is not different from the efficiency order as recorded for the old grid. This affirms that it Egbin still remains the most efficient of all the older thermal plants

Table 3: Expanded thermal plants economic load dispatch

Plants	1101 MW	1497 MW	1893 MW	2289 MW	2685 MW	3081 MW	3477 MW	3873 MW	4269 MW	4665 MW
Omotoso	60.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00
Olorunsogo	335.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00	335.00
Geregu	80.00	80.00	263.26	414.00	414.00	414.00	414.00	414.00	414.00	414.00
Afam	150.00	150.00	150.00	150.00	365.60	586.10	901.70	977.00	977.00	977.00
Egbin	220.00	394.24	663.93	944.23	1141.50	1300.00	1300.00	1300.00	1300.00	1300.00
Sapele	190.00	190.00	218.72	329.11	420.00	576.20	807.00	1020.00	1020.00	1020.00
Ugheli	145.00	145.00	145.00	145.00	145.00	145.00	145.00	145.00	145.00	972.00
Total Cost ($/h)	117485.66	130440.99	153066.11	187987.27	235184.12	302361.19	406555.88	476045.02	476045.02	1579486.31

The total generation costs of the economic dispatches of the old grid and expanded grid are reported in the Figure 1. Figure 1 is obtained from the plot of the total generation cost in $/h against the power demand in MW for both the old and the expanded (new) electricity grid as obtained from results in Table 2. It is fortunate to know that the cost of generating the same amount of Megawatt of Power in the expanded grid is significantly less than that of the old grid. The cost has an exponential and linear relationships with the old and expanded grid respectively. Initially the cost of generating lower power of 1101 MW was lower in the old system at a sum of 88840.9 $/h as against 117485.66 $/h. However, the cost of operating the old grid increased exponentially and became more than cost of operating expanded system with increase in power demand. For instance, total amounts of 7101304.26 $/h and 476045.02 $/h are required to generate same power demand of 3873 MW in the old grid and expanded grid respectively. Consequently, the total amount of 6625259.24 $/h is saved by generating 3873 MW of electricity in the expanded grid instead of the old grid

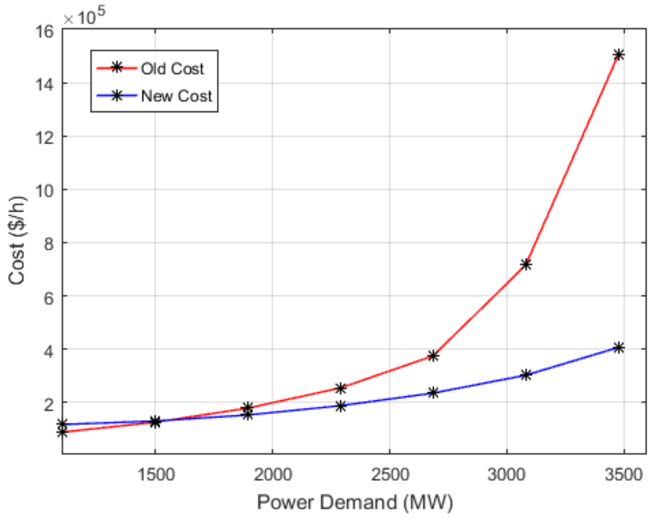

Figure 1: Total Generation cost comparison

The addition of the new thermal plants of Olorunsogo, Omotoso and Geregu to the grid reduced the load stress on the old plants thereby offsetting the total cost of generation. The old thermal plants are not brought into operation around their maximum until the new plants are not able to meet the generation demand at the operation around their limits as indicated in figures 2, 3, 4 and 5. Figures 2, 3, 4, and 5 are obtained from the plot power generation in Egbin, Afam, Sapele and Ugheli stations against the total power demand of the old and expanded grid as obtained from the results in Table 3. For instance, Egbin starts operating around its maximum limit at total load demand of 1893 MW in the old grid and 3081 MW in the expanded grid. Afam starts operating around its maximum limit at total load demand of 2685 MW in the old grid and 3873 MW in the expanded grid. Sapele starts operating around its maximum limit at total load demand of 3081 MW in the old grid and 3873 MW in the expanded grid. Ugheli starts operating around its maximum limit at total load demand of 3477 MW in the old grid but kept operation at the minimum limit in the expanded grid.

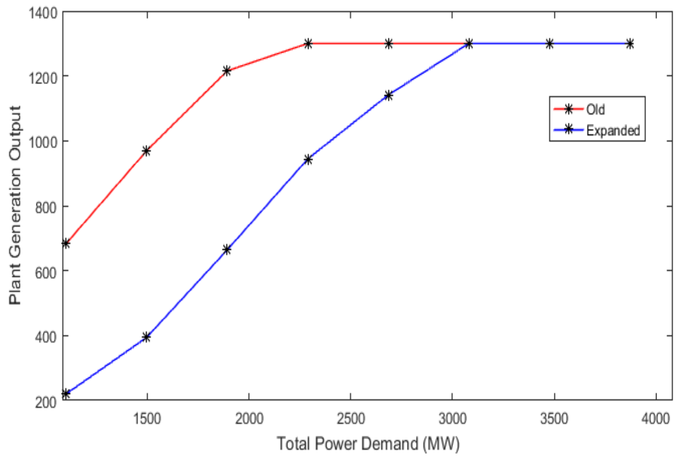

Figure 2: Egbin generation output in old and expanded grid

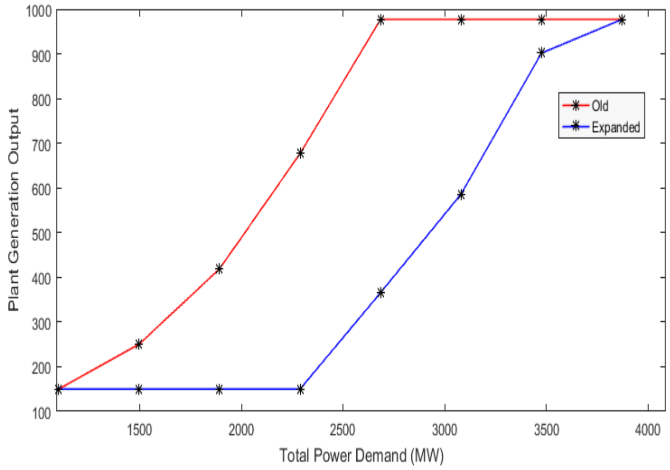

Figure 3: Afam generation output in old and expanded grid

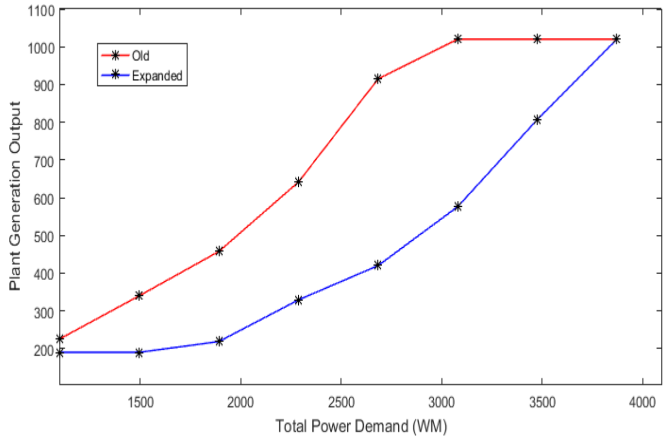

Figure 4: Sapele generation output in old and expanded grid

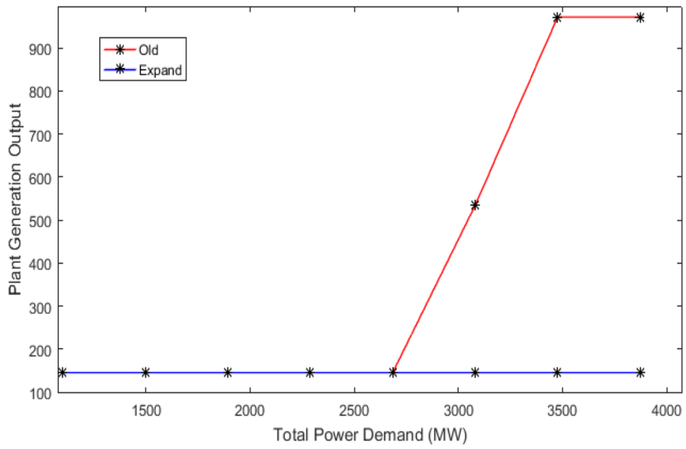

Figure 5: Ugheli generation output on old and expanded grid

4. CONCLUSIONS

Economic dispatch optimizes to determine the generation output of different plants while minimizing the operating cost. Hence, the operating cost plays an important role in the economic scheduling. A critical comparison of the total generation cost of the old and expanded grid system shows that the latter's operation is more economical and judicious.

Utilising generating plants close to the load results in lower losses. This impact of losses was included in the economic dispatch optimization carried out. This work revealed certain elements which shape power generation pattern at minimum cost. This include the plant operating efficiency, fuel cost and certainly transmission losses.

It is discovered that the proximity of thermal generating plants to gas supply does not guarantee minimum cost of generation as they are sometimes located far from the load. And, if the plant is located far from the load centre, transmission losses may be considerably higher and hence the plant may be overly uneconomical.

New generating plants (Omotoso in Ondo State, Olorunsogo in Ogun State and Geregu in Kogi State) are more efficient than older generating plants (Afam, Egbin, Ugheli and Sapele) due to wearing and proximity to the load. Consequently, it is more important and in economic interest to continue to carry out grid expansion to include more generating stations around Nigeria.. In general, operating generating plants closer to the load results in lower losses. This impact on losses must therefore be accommodated in economic dispatch optimization problem formulation.

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