# Economic And Emission Load Dispatch for The Nigerian Power System Using Improved Firefly Algorithm

NDIKILAR B. JITZI[1], U. O. ALIYU[2], O. U. OKEREKE[3]
[1, 2, 3] *Faculty, Department of Electrical and Electronics Engineering, Abubakar Tafawa Balewa University, Bauchi-Nigeria*

***Abstract- It is of paramount importance for a power system comprising of many generating units to operate under an economic platform. However, effects of generation on the environment should also be considered alongside the cost of generation. This paper employs the improved firefly algorithm to solve the economic and emission load dispatch problem for the Nigerian power system. Valve-point loading effects are considered. The two objectives are combined to form one objective function with the use of weighting factors. The price penalty factor is applied on the emission function to ensure homogeneity of the objective function. Different values of weighting factors are applied to obtain the best. Comparison analysis is carried out between results obtained and other metaheuristic techniques; Genetic algorithm (GA), Particle Swarm Optimization (PSO) and conventional Firefly Algorithm (FA). From the simulations, it is observed that the improved firefly algorithm produces the best compromise between fuel cost and emission quantities.***

***Indexed Terms- Load dispatch, Firefly Algorithm, Price Penalty Factor, Generation***

## I. INTRODUCTION

Electrical energy is of paramount importance to every growing economy and the size of electrical power systems is increasing to meet the rapid increase in demand. But the rate of increase of the generating facilities is less than the rate of increase in power demand. Hence, it is necessary to operate the power system on an economic platform, to save cost of operation. This can be done through the application of Economic Load Dispatch (ELD) techniques. The ELD is a very important aspect of the power system. The purpose of the economic load dispatch is to determine the generation of various units in a plant such that the total fuel cost is minimum and at the same time, the total demand and losses at any instance must be equal to the total generation. The common task in power system is to determine and provide an economic condition for generating units without violation of any of the system's constraints.

On the other hand, there are serious environmental concerns arising due to the pollution caused by toxic gases released from thermal units after combustion of fuel. Global warming which has been on the rise for decades is one of those negative effect caused by the emission of greenhouse gases (GHG) into the atmosphere. Greenhouse gases are those gases that allow the sun's energy to reach the earth's surface but prevent this heat from leaving the earth's surface thus leading to an increase in the earth's temperature and change in weather patterns. Some of these by-products of combustion include, Carbon dioxide ($CO_2$), Nitrogen oxides ($NO_X$), Sulphur dioxide ($SO_2$) and Particulate matter (PM).

With rapid increase in technological advancement, managing these dispatch problems simultaneously has been made possible. With the application of modern optimization techniques, the combined economic and emission load dispatch problem can be solved wherein the algorithm analyses the two aspects of the objective function and gives the dispatcher the best compromise.

## II. RELATED WORK

In [1]. the combined economic emission dispatch with Environment Based Demand Response using WU-ABC algorithm was carried out. The objective function was constructed in consideration of generation costs and pollutant emission. The emission function took the emitted quantities into account and converts their sum into operation costs through unit conversion, using a penalty factor. A multi-objective algorithm called Broyden Fletcher Goldfarb Shanno based on Augmented Lagrangian (BFGS-AL) algorithm was applied to solve the economic and environmental load dispatch problem in [2]. The IEEE-30 bus test system was used to test the algorithm. The transmission line losses were considered in the optimization process but valve point loading effects were neglected. [3]. performed a simultaneous multi-area economic-environmental load dispatch modelling with thermal and wind turbines using Multi-Objective Particle Swarm Optimization. It was established that the unpredictable nature of wind generations makes the generation dispatch process highly complex. Thus, in the developed method, the storage and additional costs were defined in the objective function of the economic dispatch problem and the mean value of wind energy density was utilized. Transmission losses, generation limits and line carrying capacity were considered as constraints. A twelve-unit thermal power plant, two wind farms and three areas were considered and the efficiency of the proposed method was evaluated based on the simulation results on the IEEE 118 test bus system. The Biogeography Based Optimization (BBO) technique was proposed in [4]. to minimize fuel cost and emissions from thermal generating units. The results obtained by BBO were compared with the results obtained by different optimization techniques such as GA, PSO, EP and DE with respect to fuel cost, solution time and convergence criteria. [5]. presented an elitist technique, the second version of the non-dominated sorting genetic algorithm (NSAGII) to solve the DEED problem. Contraints considered were; valve point loading effect, ramp rate limits and prohibited zones. A fuzzy based membership function value assignment method was suggested to provide the best compromise solution. A ten-unit system was used to verify the effectiveness of the proposed approach. [6] presented an emission inventory of electricity generation from thermal plants in Nigeria. An emission factor approach was used in this study to quantify the emission of uncontrolled air pollutant discharged into the atmosphere from all existing thermal plants. The pollutants examined were carbon monoxides (CO), oxides of Nitrogen ($NO_X$), particulate matter, Sulphur dioxide ($SO_2$) and volatile organic compounds (VOCs). From the specific data, the study discovered that, the higher the production capacity, the higher the emission emitted.

## III. ECONOMIC AND EMISSION LOAD DISPATCH

### a. Economic Model

The economic dispatch (ED) problem is represented as a non-linear expression with valve-loading effects and is subject to equality constraints of power balance and inequality constraints of plant upper and lower bounds.

Minimize

$$\boldsymbol{F}(\boldsymbol{P_{Gi}}) = \sum_{i=1}^{NG} (a_i + b_i(P_{Gi}) + c_i(P_{Gi})^2) + |d_i * sin(f_{s1}(P_{Gi}{}^{min} - P_{Gi}))| \quad \dots (1)$$

Subject to:

$$\sum_{i=1}^{NG}(P_{Gi}) = P_D + P_L \quad \dots (2)$$

Where

$$P_{L=}\, B_{00} + \sum_{i=1}^{NG} B_{0i}(P_{Gi}) + \sum_{i=1}^{NG}(P_{Gi})\left(B_{ij}\right)\left(P_{Gj}\right) \quad \dots (3)$$

$$P_{Gi}^{Min} \leq P_{Gi} \leq P_{Gi}^{Max} \quad \dots (4)$$

Where NG is the number of thermal generating units, $F(P_{Gi})$ is the total fuel cost, $P_{Gi}$ is the real power output of unit i, $a_i$, $b_i$, $c_i$, $e_i$ $f_i$ are the fuel cost coefficients. $P_D$ is the total demand; $P_L$ is the transmission line losses. $P_{Gi}^{Min}$ and $P_{Gi}^{Max}$ are the lower and upper bounds of the $i^{th}$ unit respectively. The first constraint (2) which is called power balance constraint is an equality constraint and while the second constraint (4) is the inequality constraint denoting the thermal unit's operational limits.

### b. Emission model

The emissions released by the thermal generating plants as a result of the combustion of fossil fuel to the environment to be considered in this paper are $CO_2$, $SO_2$, $NO_X$ and PM. And they have very adverse effects on the ecosystem. It is also worth noting that the quantity of emission produced depends on; the type of fuel used, control devices installed, age of machines and amount of electricity generated.

$$\boldsymbol{E_{Gi}} = \sum_{i=1}^{NG}(\alpha_i + \beta_i(P_{Gi}) + \gamma_i(P_{Gi})^2) + \lambda_i * exp(\delta_i P_{Gi}) \quad \dots (5)$$

$E(P_{Gi})$ is the quantity of emissions produced in Kg/hr, while $\boldsymbol{\alpha}$, β, $\boldsymbol{\gamma}$, $\boldsymbol{\xi}$, $\boldsymbol{\lambda}$, **δ** are the emission coefficients.

### a. Combined economic and emission model

The price penalty factor $h_i$, is integrated for the various emissions accounted for in this work so as to come up with a single and homogenous objective function. The weighting factor (w) is also introduced in the objective function. The weighting factor defines the relative importance of one component of the objective function with respect to the other. It is dimensionless and ranges from 0-1.

$$F_{Ti}(P_{Gi}) = wF(P_{Gi}) + (1-w)hi * E(P_{Gi}) \quad \ldots (6)$$

Where $F_{Ti}$ is the total cost in N/hr, $h_i$ is the price penalty factor in N/kg to ensure homogeneity of the objective function.

b. Price penalty factors

The price penalty factor is formulated by taking the ratio of the fuel cost and the emission value in the corresponding generators and is given as follow;

$$h_i = \frac{F(P_{Gi})}{E(P_{Gi})} \quad \ldots (7)$$

Four different price penalty factors are considered in this paper

i. The Max-Max Price Penalty Factor

$$h_i = \frac{F(P_{Gi})^{Max}}{E(P_{Gi})^{Max}} \quad \ldots (8)$$

ii. The Max-Min Price Penalty Factor

$$h_i = \frac{F(P_{Gi})^{Max}}{E(P_{Gi})^{Min}} \quad \ldots (9)$$

iii. The Min-Max Price Penalty Factor

$$h_i = \frac{F(P_{Gi})^{Min}}{E(P_{Gi})^{Max}} \quad \ldots (10)$$

iv. The Min-Min Price Penalty Factor

$$h_i = \frac{F(P_{Gi})^{Min}}{E(P_{Gi})^{Min}} \quad \ldots (11)$$

## IV. METHODOLOGY

The metaheuristic algorithm considered in this work is the Improved Firefly Algorithm (IFA) which developed by modifying the traditional Firefly Algorithm formulated by Yang Xhe-She in 2008. The fundamental principles on the traditional firefly was formulated are;

i. All fireflies are unisex and they move towards more attractive and brighter ones regardless of their sex.
ii. The degree of attractiveness of a firefly is proportional to its brightness which decreases as the distance from the other firefly increases due to the fact that the air absorbs light. If there is not a brighter or more attractive firefly than a particular one, it will then move randomly.
iii. The brightness or light intensity of a firefly is determined by the value of the objective function of a given problem. The fireflies with lower brightness level moves to other ones with higher brightness level.

Each firefly corresponding to each optimal solution will own its brightness corresponding to the fitness function of the optimal solution. The action that the fireflies with lesser brightness will look for and get to other fireflies producing higher brightness level is similar to the newly produced solutions based on old solutions, with a better fitness function. Consequently, in firefly algorithm, each old solution can be produced several times depending on the comparison of its brightness with other ones. As a result, only one new solution of each old solution is kept based on the comparison of fitness function.

a. Distance

In calculating the distance between the considered solution i and another better solution to determine the radius, the best solution $X_{Gbest}$ is recommended for calculating the radius as expressed below.

$$r_{ibest} = \sqrt{(X_i - X_{Gbest})^2} \quad \ldots (12)$$

b. Attractiveness

The updated distance is employed to be substituted in another equation to determine the new attractiveness. Then the new position for the i^th^ considered firefly can be determined corresponding to the generation of a new solution of the i^th^ solution. The procedure of generating a new solution is carried out as;

$$\beta_r = \beta_{o*}\mathrm{Exp}(-\gamma \boldsymbol{r_{ij}}^2) \quad \ldots (13)$$

Where, r is the distance between any two fireflies, $\beta_0$ is the initial attractiveness at r=0, and $\gamma$ is an absorption coefficient which controls the decrease of the light intensity.

c. Updated step size

The expression below used to generate the updated step size and obtain lower solution fitness than those of firefly algorithm.

$$\Delta X_{1ij} = X_{Gbest} - X_{GWorst} \quad \ldots (14)$$

$$\Delta X_{2ij} = X_j - X_i + X_{r1} + X_{r2} \quad \ldots (15)$$

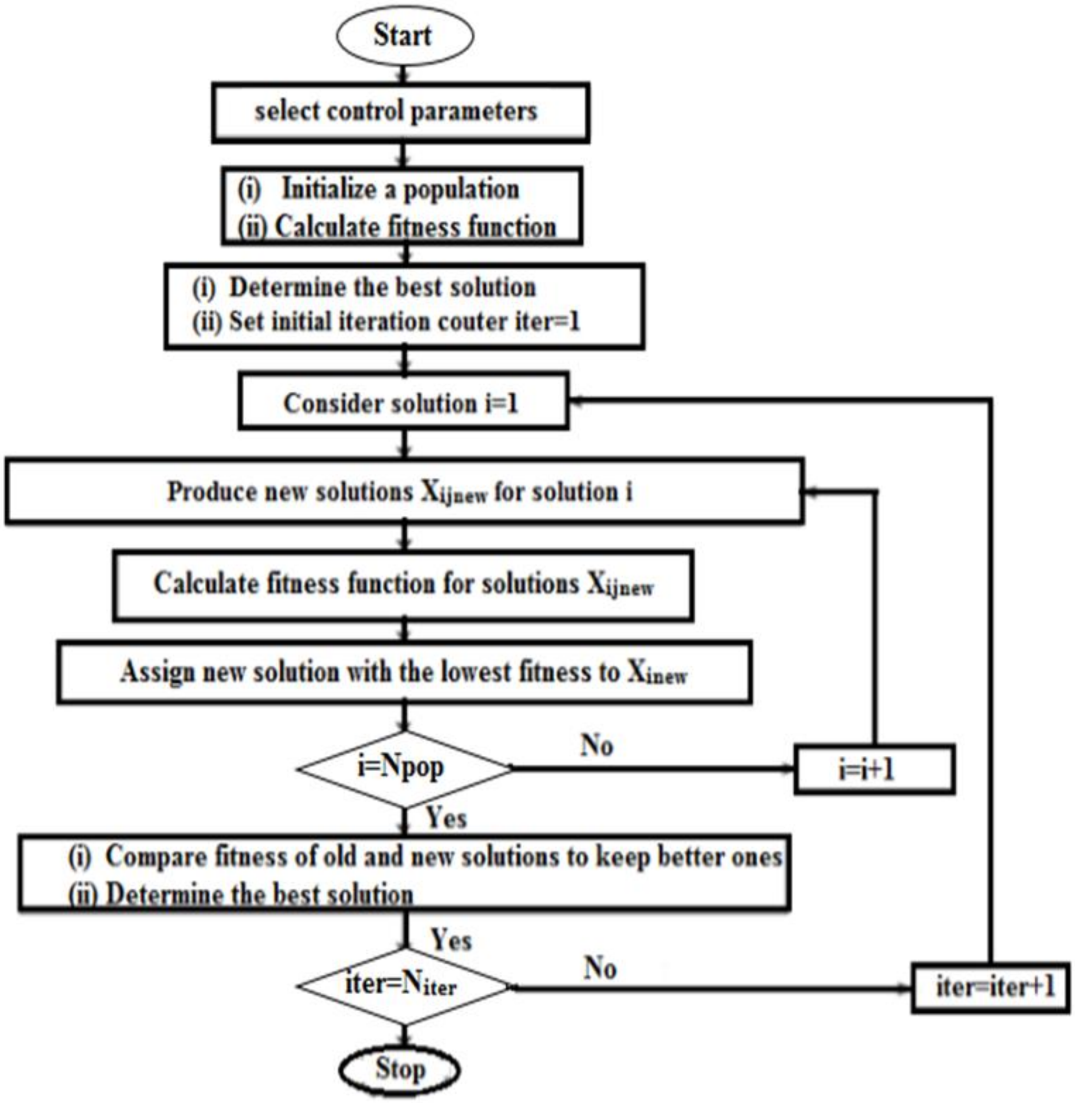
The first updated step size $\Delta X_{1ij}$ is less than the second step size $\Delta X_{2ij.}$ The first facilitate exploitation by narrowing the search zone near old solutions while the second can expand exploitation (exploration) to avoid falling into the same solution.

d. Movement

The movement of a firefly i which is attracted by a more attractive (brighter) firefly j is given by the following equation. A normal distribution is used instead of the uniform distribution to calculate the new position of the firefly in order to diversify the search zone.

$$\boldsymbol{X_{i+1}} = \boldsymbol{X_i} + \beta_{o*}\mathbf{Exp}(\text{-}\gamma \boldsymbol{r_{ij}}^2) * (\boldsymbol{X_{Gbest}} - \boldsymbol{X_i}) + \alpha * (rand - \tfrac{1}{2}) \quad \ldots (10)$$

Figure 1 below is a pictorial representation of the improved firefly algorithm.




Source: Thang *et al*. (2018)

Figure 1: Flow chart of improved firefly algorithm

## V. RESULTS

Table 1: Price Penalty Factor

| S/N | Price penalty Factors | Output (MW) |
|---|---|---|
| 1 | Max-Max | 2,691.3 |
| 2 | Max-Min | 2,632.0 |
| 3 | Min-Max | 2,619.4 |
| 4 | Min-Min | 2,658.0 |

Table 2: Allocations for different weighting factors at 2500MW

| S/N | Station | Economic load dispatch (ω=1) | Emission load dispatch (ω=0) | Economic and emission load dispatch (ω=0.5) |
|---|---|---|---|---|
| 1 | Aes | 177.4065 | 71.5626 | 129.8278 |
| 2 | Afam IV | 258.1022 | 245.3162 | 183.3824 |
| 3 | Egbin | 125.3582 | 303.7513 | 207.4987 |
| 4 | Trans-amadi | 26.7065 | 8.4995 | 25.5607 |
| 5 | Afam IV-V | 94.6528 | 67.1295 | 238.6688 |
| 6 | Alaoji | 75.9200 | 38.9051 | 66.3851 |
| 7 | Delta II-III | 59.3777 | 105.4157 | 69.6705 |
| 8 | Delta V | 128.6891 | 208.8580 | 24.7536 |
| 9 | Geregu Nipp | 122.1612 | 141.9726 | 123.4706 |
| 10 | Geregu | 436.7304 | 94.1582 | 178.0919 |
| 11 | Ibom | 94.8273 | 63.8323 | 48.5313 |
| 12 | Ihovbe Nipp | 111.3352 | 104.2751 | 99.5892 |
| 13 | Okapi | 329.7748 | 469.1502 | 263.2501 |
| 14 | Olorunsogo | 12.3263 | 11.0114 | 116.5018 |
| 15 | Omoku | 28.2853 | 16.9417 | 52.3552 |
| 16 | Omotosho Nipp | 67.7819 | 39.8051 | 184.7741 |
| 17 | Omotosho | 30.1313 | 164.6205 | 166.6340 |
| 18 | Rivers ipp | 146.1202 | 125.4725 | 103.2351 |
| 19 | Sapelle st | 36.2059 | 34.0823 | 135.4553 |
| 20 | Sapelle gt | 189.8729 | 201.5683 | 35.6168 |
| 21 | Olorunsogo Nipp | 31.0035 | 94.0427 | 113.0447 |
| | Fuel cost (N/hr) | 3,596,200 | 3,835,000 | *3,791,000* |
| | $CO_2$ (Kg/hr) | 120,480.0 | 114,930.0 | *117,960.0* |
| | $NO_X$ (Kg/hr) | 293.7548 | 280.2163 | *287.7033* |
| | $SO_2$ (Kg/hr) | 21.6968 | 20.6968 | *21.2416* |
| | PM (Kg/hr) | 14.0275 | 13.381 | *13.7333* |

Table 3: Optimal Allocation for 4000MW, 5000MW and 6000MW

| S/N | POWER STATION | 4000MW | 5000MW | 6000MW | $P_{min}$ (MW) | $P_{max}$ (MW) |
|---|---|---|---|---|---|---|
| 1 | AES | 113.6603 | 79.6189 | 242 | 51 | 242 |
| 2 | AFAM IV | 361.6687 | 607.9682 | 656 | 45 | 656 |
| 3 | EGBIN ST(GAS) | 739.1405 | 742.3478 | 1100 | 118 | 1100 |
| 4 | TRANS AMADI | 27.6949 | 12.5828 | 19.7 | 4 | 31 |
| 5 | AFAM IV-V | 288.4527 | 381.4889 | 453 | 24 | 453 |
| 6 | ALAOJI NIPP | 74.3535 | 66.2961 | 58.9 | 34 | 87 |
| 7 | DELTA II-III | 104.6354 | 71.7715 | 19.7 | 10 | 110 |
| 8 | DELTA IV | 299.0367 | 380.6842 | 434 | 22 | 434 |
| 9 | GEREGU NIPP | 223.759 | 216.2418 | 271.9 | 94 | 272 |
| 10 | GEREGU | 291.3757 | 342.2282 | 450 | 14 | 450 |
| 11 | IBOM | 53.2629 | 195.8447 | 90.8 | 10 | 101 |
| 12 | IHOVBE NIPP | 103.4197 | 111.1956 | 112.3 | 91 | 120 |
| 13 | OKPAI | 275.0243 | 430.1614 | 475 | 100 | 475 |
| 14 | OLORUNSOGO | 182.9223 | 267.3707 | 293 | 10 | 293 |
| 15 | OMOKU | 45.5589 | 36.6957 | 64.2 | 3 | 65 |
| 16 | OMOTOSHO NIPP | 143.3603 | 192.8875 | 225 | 20 | 225 |
| 17 | OMOTOSHO | 348.2408 | 461.2613 | 480 | 29 | 480 |
| 18 | RIVERS IPP | 97.7694 | 90.4353 | 160 | 20 | 160 |
| 19 | SAPELE (ST) | 149.445 | 134.6193 | 223 | 33 | 223 |
| 20 | SAPELE GT(NIPP) | 186.2521 | 319.888 | 373 | 30 | 373 |
| 21 | OLORUNSOGO NIPP | 223.4018 | 398.657 | 422 | 31 | 422 |

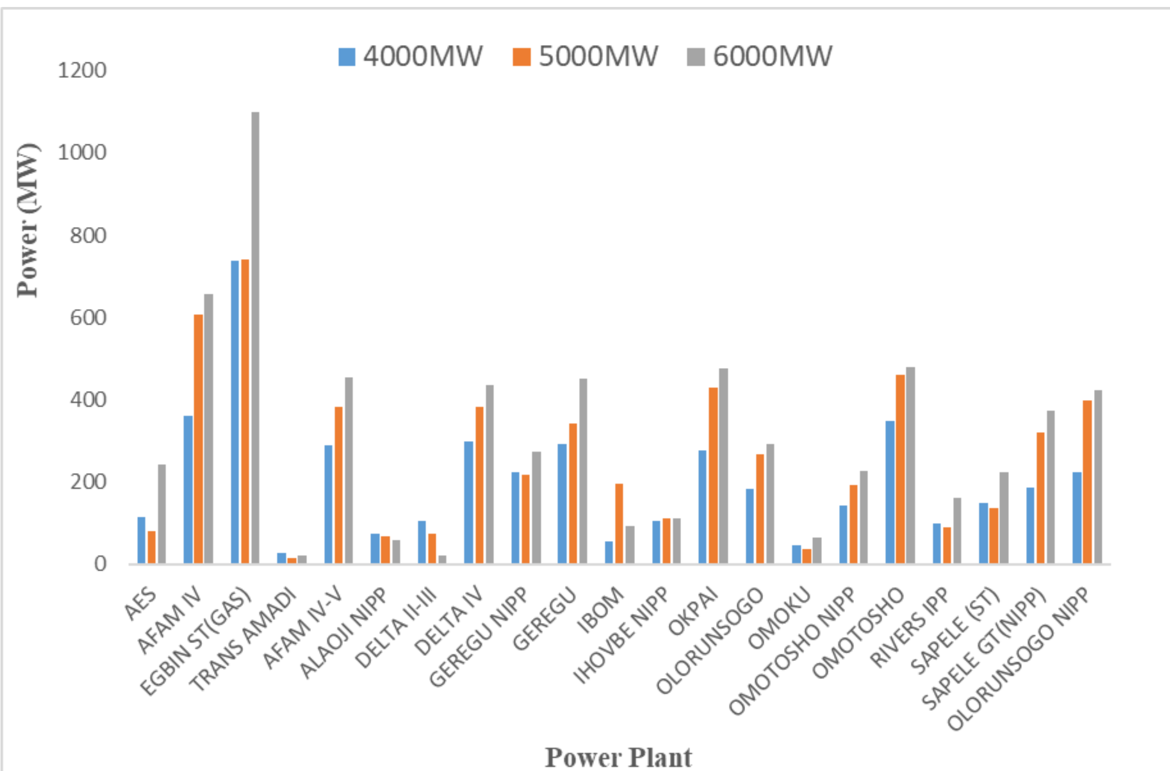



Figure 1: Optimal Allocation for 4000MW, 5000MW and 6000MW

Table 4: Comparison of optimization techniques at 2500MW

| S/N | POWER PLANT | GA | PSO | | FA | IFA |
|---|---|---|---|---|---|---|
| 1 | AES | 55.9580 | 149.7333 | | 136.6588 | 129.8278 |
| 2 | AFAM IV | 179.8223 | 541.3950 | | 231.9705 | 183.3824 |
| 3 | EGBIN ST(GAS) | 190.4600 | 121.1194 | | 212.1059 | 207.4987 |
| 4 | TRANS AMADI | 15.1567 | 28.6643 | | 8.0199 | 25.5607 |
| 5 | AFAM IV-V | 59.3641 | 61.4773 | | 193.6141 | 238.6688 |
| 6 | ALAOJI NIPP | 45.3778 | 34.1192 | | 64.8705 | 66.3851 |
| 7 | DELTA II-III | 38.5311 | 61.1993 | | 48.7584 | 69.6705 |
| 8 | DELTA IV | 53.9457 | 22.0000 | | 116.3625 | 24.7536 |
| 9 | GEREGU NIPP | 268.7952 | 140.0508 | | 188.1534 | 123.4706 |
| 10 | GEREGU | 450.0000 | 287.0630 | | 112.8001 | 178.0919 |
| 11 | IBOM | 51.5232 | 42.7905 | | 46.7341 | 48.5313 |
| 12 | IHOVBE NIPP | 97.2412 | 91.0000 | | 96.8972 | 99.5892 |
| 13 | OKPAI | 163.7388 | 177.8049 | | 259.5216 | 263.2501 |
| 14 | OLORUNSOGO | 229.8148 | 293.0000 | | 66.2876 | 116.5018 |
| 15 | OMOKU | 31.8288 | 40.5393 | | 40.7786 | 52.3552 |
| 16 | OMOTOSHO NIPP | 129.8019 | 163.8632 | | 130.4197 | 184.7741 |
| 17 | OMOTOSHO | 162.4469 | 240.6234 | | 117.4623 | 166.6340 |
| 18 | RIVERS IPP | 156.0696 | 27.4589 | | 127.2110 | 103.2351 |
| 19 | SAPELE (ST) | 222.1271 | 33.0000 | | 92.7675 | 135.4553 |
| 20 | SAPELE GT(NIPP) | 109.8957 | 30.0000 | | 219.9624 | 35.6168 |
| 21 | OLORUNSOGO NIPP | 31.0000 | 40.8583 | | 108.9694 | 113.0447 |
| | Total Power (MW) | 2690.1 | 2,627.7 | | 2,620.3 | 2,619.1 |
| | $CO_2$ (Kg/hr) | 119.110 | 118.520 | | 118,240.0 | 117,960.0 |
| | $NO_X$ (Kg/hr) | 288.3211 | 287.9433 | | 287.7321 | 287.7033 |
| | $SO_2$ (Kg/hr) | 22.2974 | 22.1822 | | 21,3122 | 21.2416 |
| | PM (Kg/hr) | 14.2284 | 13.7899 | | 13.7543 | 13.7333 |
| | Fuel Cost (N/hr) | 4,569,200 | 4,240,900 | | 3,907,000 | 3,791,000 |

## CONCLUSION

The economic and emission load dispatch was successfully carried out using the improved firefly algorithm on the Nigerian Power System to ascertain allocations of the thermal power plants. Different price penalty factors were applied and the Min-Max penalty factor produced the optimal results. Three weighting factors (ω=0, ω=0.5, ω=1) were used and the best compromise was achieved with ω=0.5. The results obtained satisfies all the constraints under consideration as seen in Table 3. Different optimization techniques were used to compare the results and the IFA was found to be the best in terms of minimal fuel cost and emissions released into the atmosphere.

## REFERENCES

[1] Ho-Sung Ryu & Mun-Kyeom Kim. (2020). Combined Economic Emission Dispatch with Environment-Based Demand Response Using WU-ABC Algorithm. *Energies*,

[2] El Hachmi Talbia, Lhoussine Abaalia, Rachid Skourib and Mustapha El Moudden. (2020). Solution of Economic and Environmental Power Dispatch Problem of an Electrical Power System using BFGS-AL Algorithm. *International Workshop on the Advancement Model Driven Enginnering* (pp. 857-862). Warsaw: Elsevier B.V.

[3] Farzad Habibi, Farshad Khosravi, Saeed Kharrati and Shahram Karimi. (2020). Simultaneous Multi-area Economic-Environmental Load Dispatch Modeling in Presence of Wind Turbines by MOPSO. *Journal of Electrical Engineering & Technology* , 1-14.

[4] Sunil Kumar Goyal, Neeraj Kanwar, Manish Shrivastava, Amit Saraswat and O. P. Mahela. (2020). Economic Load Dispatch with Emission and Line Constraints using Biogeography Based Optimization Technique. *International Conference on Intelligent Engineering and Management (ICIEM)* , (pp. 471-476). Carleton.

[5] Ahmed Torchani, Attia Boudjemline, Hatem Gasmi, Yassine Bouazzi & Tawfik Guesmi. (2019). Dynamic Economic/Environmental Dispatch Problem Considering Prohibited Operating Zones. *Engineering, Technology & Applied Science Research, 9*, 4586-4590.

[6] Adesanmi A. J., Badmos S. A., Gbadebo O. A. & Sonibare J. A. (2019). Emission Inventory of Electricity Generation From Thermal Power Plants In NIgeria. *Global Scientific Journals, 7*(2), 140-150.

[7] Ya'U Haruna Shu'aibu, Yakubu Adajah Yisah, G. A. Bakare, Mohammed Sani Haruna. (2017). Optimal Economic Load Dispatch of the Nigerian Thermal Power Stations Using Particle Swarm Optimization. *International Journal of Engineering and Sciences (IJES)*, 17-23.

[8] Eke, M. N. (2014). Long Term Energy Performance of Egbin Thermal Power Plant, Nigeria. *Nigerian Journal of Technology (NJOTECH), 33*(1), 97-103.

[9] Abedinia O., N. Amjady & Mohammad S. Naderi . (2012). Multi-objective Environmental/Economic Dispatch Using Firefly Technique . *Electrical Engineering Department, Semnan University, Semnan, Iran*, 1-6.

[10] J. N. Ndunagu, Vincent Kenechi Abanihi & S.Ikheloa. (2020). Economic Load Dispatch for Nigerian Power Network Using a Hybrid of Evolutionary Programming and Efficient Particle Swarm Optimization. *FUW Trends in Science and Technology Journal*, 697-702.

[11] Nnaemeka Vincent Emodi & Kyung-Jin Boo. (2015). Decomposition Analysis of Carbon Dioxide Emission From Elelctriciy Generation in Nigeria. *International Jurnal of Energy Economic and Policy*, 565-573.

[12] Nwohu M.N. and Osaremwinda Osarobo Paul. (2017). Evaluation of Economic Load Dispatch Problem in Power Generating Stations by the Use of Ant Colony Search Algorithms. *International Journal of Research Studies in Electrical and Electronics Engineering (IJRSEEE) Volume, 3*(1), 20-29.

[13] Thang Trung Nguyen, Nguyen Vu Quynh and Le Van Dai. (2018). Improved Firefly Algorithm: A Novel Method for Optimal Operation of Thermal Generating Units. (M. Scarpiniti, Ed.) *Hindawi*, 1-23.

[14] Xin-She Yang. (2010). Firefly Algorithms for Multimodal Optimization. *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge*, 1-11.