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Evaluation of Optimal Power Dispatch of the Nigerian Power System Using Particle Swarm Technique

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ABSTRACT: *This paper presented Particle Swarm Optimization (PSO) approach for solving Economic Load Dispatch (ELD) problem for interconnected generating units. It considered most practical operation constraints of the generators. It aims at finding the short-term optimal real power output levels of a number of already committed/online generating units to meet the system load demand at the lowest possible cost while satisfying the system transmission and operation constraints. Conventional optimization methods assume the generator cost curves to be continuous and monotonically increasing, but in practice, generators have variety of nonlinearities in their cost curves; making this assumption inaccurate. The approximate dispatch results cause a considerable amount of revenue loss. PSO technique considers the nonlinear characteristics of a generator such as ramp rate limits, power balance constraints with maximum and minimum operating limits and prohibited operating zone for actual power system operation. PSO based ELD was performed for the IEEE 6-units test system and Nigerian power grid. The results obtained in this work were compared with the results obtained from literature for the same test systems within a difference of 2.7229%. Also, the PSO gave a lower cost of operation while satisfying the constraints. This comparison was necessary to validate the accuracy of the algorithm used in this work. PSO is confirmed to be a very fast and accurate algorithm, thus very efficient for carrying out economic load dispatch. The algorithm, MATLAB codes and results obtained in this work can be deployed by the power system operators to aid in their day-to-day operations.*

Keywords: *optimization, particle swarm optimization, economic load dispatch, fuel-cost curve, ramp rate limit, prohibited operating zone, IEEE 6-unit test system, Nigerian power grid*

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I. INTRODUCTION

The optimum solution of the practical economic load dispatch problem is one of the most widely discussed and researched issues of power system planning and operation. The modern power system around the world has grown so much in complexity of interconnection and power demand. The focus has shifted towards enhanced performance, increased customer focus, low cost, reliable and environment friendly/pollution free power generation [1]. Presently, scarcity of energy resources, increasing power generation cost and environmental concern necessitates optimal economic dispatch.

Economic load dispatch is basically an optimization problem. Optimization is the act of obtaining the best result under given circumstances [2]. Traditional algorithms like equal lambda iteration, base point participation factor, gradient method and Newton method can solve ELD problems effectively, if and only if the fuel-cost curves of the generating units are piece-wise linear and monotonically increasing [3]. Practically, the input to output characteristics of the generating units are highly non-linear, non-smooth and discrete in nature owing to prohibited operating zones, ramp rate limits and multi-fuel effects [3]. As a result of this inherent non-linearity, the practical ELD problem becomes a challenging non-convex optimization problem, which is difficult to solve using the traditional methods. Methods like dynamic programming (DP), genetic algorithm (GA), evolutionary programming (EP), artificial intelligence (AI), and particle swarm optimization (PSO) solve non-convex optimization problems efficiently and often achieve a fast and near global optimal solution [1].

1.1 Overview of The Nigeria Power System

Sources of electricity in Nigeria for the last 40 years varied from hydroelectric power stations in the north, gas-fired thermal stations in the south and very few coal-fired stations in Oji, Enugu State, with hydroelectric power system and gas-fired plants taking precedence. Though Oji coal-fired station has been scrapped.

The Nigerian power system is sub divided into six (6) generating companies (20% owned by the Nigerian Federal Government and 80% owned by private firms), one (1) transmission company (100% owned by the Nigerian Federal government called the TCN - Transmission Company of Nigeria) and 11 distribution companies [4] owned by private firms.

Basically, electric power is generated in Nigeria within the range of 11kV to 25kV, transmitted at 132kV and 330kV, distributed at 11kV and 33kV while homes are serviced with 3 phase 415V and consumed at 240V

Fig. 1. shows the one-line diagram of the 330kV Nigerian national grid indicating various generation buses, load buses, transmission lines and their various interconnection. Table 1. Shows various generating stations located within the national grid network, their capacities and locations.

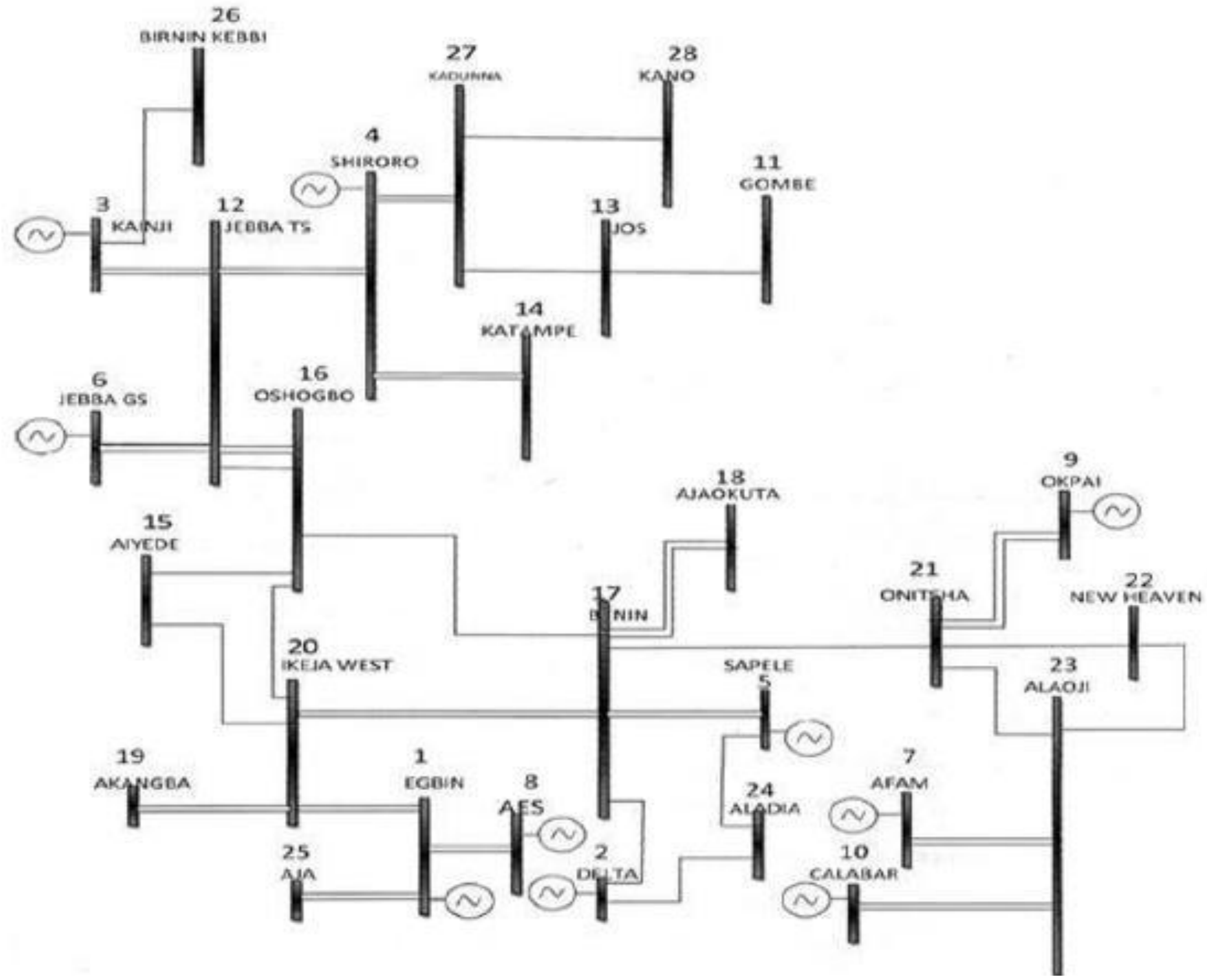

Figure 1. One-line diagram of the existing 28 bus 330kV Nigerian transmission grid [5]

1.3 Statement of the Problem

One of the major challenges facing power utilities is meeting customers' load demand at minimal cost while maintaining stability on the network. This is an optimization problem that needs a solution. A reliable power system consists of many generating units, each of which has its own characteristic operating parameters [7] and making assumptions of these unique parameter leads to computation errors.

Table 1. The various generating stations on the Nigerian 330kV grid, their capacity and location in [6].

S/N	GENERATING STATION	LOCATION	TURBINE	INSTALLED CAPACITY (MW)
1	Egbin	Lagos	Steam	1320
2	Delta	Delta	Gas	912
3	Kainji	Niger	Hydro	760
4	Shiroro	Niger	Hydro	600
5	Jebba	Niger	Hydro	504
6	Afam	Rivers	Gas	726
7	Sapele	Delta	Gas	1020
8	AES	Lagos	Gas	250
9	Okpai	Delta	Gas	900
10	Calabar	Cross River	Gas	480

The economic dispatch problem is the minimization of the operating cost of the already committed generating units while satisfying the load demand and the various generator operating constraints. This involves determining the real power output of each committed unit that will give the least operating cost.

1.4 Objectives of the Research

The objective of this work is to minimize total operating cost of the generating units in the Nigerian power system using particle swam optimization considering the practical operation constraints of generators. The specific objectives include:

i. To study the Economic Dispatch Problem and Particle Swarm Optimization technique.
ii. To demonstrate, with graphic user interface (GUI) and MATLAB simulation, how PSO converges at the global optimum (minimum point) applying standard mathematical functions.
iii. To use MATLAB to simulate and demonstrate the capability of PSO in finding the economic solution/least cost for the optimal dispatch of power generation using IEEE standard test system (6-generating units) data.
iv. Perform ED with PSO technique in MATLAB for the Nigerian power system using the Nigerian power grid data obtained from referenced past materials.

II. LITERATURE REVIEW

Optimization methods as solution to real life problems can be traced to the days of Newton, Lagrange, and Cauchy. Newton and Leibnitz developed differential calculus to analyze and solve problems of real system, calculating their optimum performance points [2]. The basics for calculus of variations, which deals with the minimization of functions, were laid by Bernoulli, Euler, Lagrange, and Weirstrass. Other method of optimization for constrained problems, which involves the addition of unknown multipliers, became known by the name of its inventor, Lagrange.

Despite these early contributions, very little progress was made until the middle of twentieth century, when high-speed digital computers made implementation of the optimization procedures possible and stimulated further research on new methods. Spectacular advances followed, producing a massive literature on optimization techniques. This advancement also resulted in the emergence of several well-defined new areas in optimization theory [2].

The need by scientists and engineers to optimize more than one objective or goal while satisfying the physical constraints led to the development of multi-objective programming method while the foundations of game theory were laid by von Neumann in 1928 and since then the technique has been applied to solve several mathematical economics and military problems [2]. Only during the last few years has game theory been applied to solve engineering design problems. There is no single method available for solving all optimization problems efficiently. Hence, several optimization methods have been developed for solving different types of optimization problems [2].

Historically, economic dispatch (ED) is being carried out since 1920. It was the time when engineers were concerned with the problem of economic allocation of generation or the proper division of the load among the generating units available. Prior to 1930, the methods in use includes: the base load method and best point loading. It was recognized as early as 1930, that the incremental cost method, later known as the equal incremental cost method yielded the most economic results, the analogue computer was developed to solve the coordination equations, a transmission loss penalty factor computer was developed in 1954, an electronic differential analyzer was developed and used in ED for both offline and on-line use by 1955, while the digital computer was investigated in 1954 for ED and is being used to date [8].

2.1 Economic Load Dispatch

This is a power system operation which aims at determining the required power output of each of the already committed generating units in the grid such that the total fuel cost is minimized while the current load demand is adequately satisfied and the operational, system and environmental constraints are adequately satisfied. After computing the optimal level of generation of each of the generators, the power output of the generators is controlled to the required optimal levels. Economic load dispatch (ELD) is applied to obtain optimal fuel cost, while satisfying system constraints, and generator scheduling for hourly anticipated load within a period of 24 hours.

ELD is one of the important optimization problems in advanced power system network. It is very crucial for power system planning and operation. The role of ELD in relation to other power system studies can be elaborated with a simple diagram as shown in Fig. 3. It gives ‘a time-horizon perspective of power-system studies [9]. Suppose it is forecasted that the load demand in certain number of years from now will increase beyond the available capacity, then new power plant (s) will be required in future. The experts are expected to decide on its required capacity, type and where the plant has to be located within the network to deliver optimally [10]. Once decided properly, its construction will start ahead of time, so that the plant is available within the expected time. This is a typical long-term study of power systems.

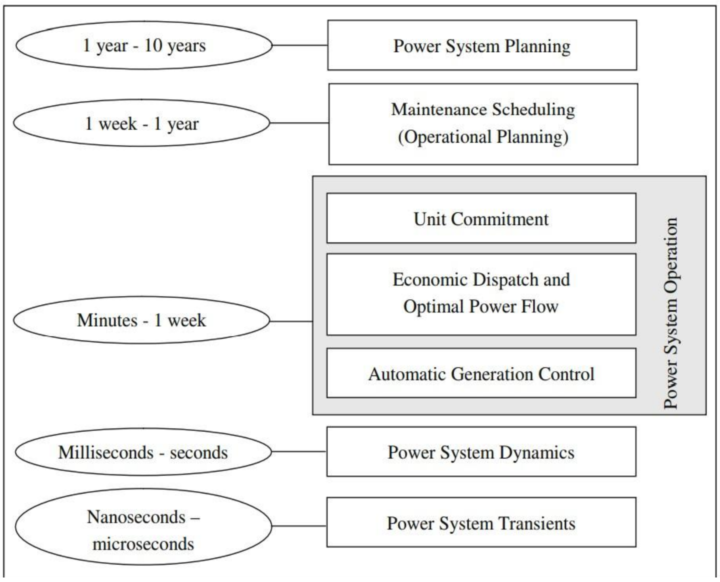

Figure 2. A time-horizon perspective of power system studies [10]

III. METHODOLOGY

3.1 Formulation of Economic Dispatch Problem

The ED problem is essentially a constrained optimization problem in which the total operating/fuel cost of all the online generating units of a power plant has to be minimized while determining the power output level of each of the generating units over a specific period of time. The constraints are in the form of equalities and inequalities that need to be fulfilled while solving the ED problem.

The Objective Function is the total fuel cost; which also incorporates the operation and maintenance cost, staff salaries in its model.

$$F_t = \sum F_i(P_i) \qquad (1)$$

To solve ED problem, the basic constrained optimization problem at specific operating interval can be modified as

$$Minimize \quad F_t = \sum F_i(P_i)$$

(2)

where F_T is the total fuel cost; F_i (P_i) and P_i are the cost function and the real power output of generator ‘i’, respectively.

The fuel cost of each generator is usually presented by a single quadratic cost function which is expressed as

$$\sum F_i(P_i) = \sum(a_i + b_iP_i + c_iP_i^2) \qquad (3)$$

where a_i, b_i and c_i denote the cost coefficients of the i-th generator.

3.1.1 Transmission Losses Consideration

When transmission distance is 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 large interconnected network where power is transmitted over long distances with low density areas, transmission losses are major factor and affect the optimum dispatch of generation.

One common practice for including the effect of transmission losses is to express the total transmission loss as a quadratic function of the generator power outputs. The simplest quadratic form is

$$P_L = \sum P_i B_{ij} P_j \qquad (4)$$

A more general formula containing a linear term and constant term, referred to as Kron's loss formula [14] is shown in Equation 5.

$$P_L = \sum P_i B_{ij} P_j + \sum B_{0i} P_i + B_{00}$$

(5)

B_{ij} are called the loss coefficients or B-coefficient, which are assumed to be constant for a base range of loads, and reasonable accuracy is expected when actual operating conditions are close to the base case conditions used to compute the coefficients.

3.1.2 Practical Operation Constraints of a Thermal Generating Unit

Practically, the operating range of all online units is restricted by their Power Generation Limits, Ramp Rate Limits (RRL), Prohibited Operating Zone (POZ), the limit of the power generation, the balance constraints and the transmission with losses consideration as previously explained. Hence all the constraints stated must be taken into account to achieve true economic operation.

i. Valve Point Loading Effects (VPL)

In large steam turbine generators due to the sequential opening of a number of steam admission valves to meet the ever-increasing demand, the input–output characteristics of a generating unit vary from convex to nonconvex. This results in nonlinear, nonconvex and non-smooth cost curves. In order to incorporate the VPL effects, a higher-order nonlinearity is introduced into the quadratic cost function [11]. The objective function (to be minimized) involving the cost function taking into account the VPL effects is expressed by

$$\text{Minimize} \quad F_t = \sum F_i(P_i) \qquad (6)$$

$$F_t = \sum\left(a_i + b_i P_i + c_i P_i^2 + \left|e_i * \sin\left(f_i * \left(P_{i,min} - P_i\right)\right)\right|\right) \qquad (7)$$

where e_i and f_i represent the ith generating unit's cost coefficients reflecting the VPL effects [11]. Consideration of ripples in the heat-rate curve of boilers in the form of recurring rectified sinusoidal term into basic quadratic cost curve introduces multiple minima thus making the ED problem nonconvex and nonlinear. While minimizing F_t , operational limitations and constraints should be taken into consideration to ensure the most feasible and optimal solution

ii. Evaluation Function

For the purpose of this research work, penalty function method was employed for the formulation of evaluation function which was minimized with chosen optimization algorithm.

The evaluation functions are for evaluating the fitness of each individual particle in the population. The quality of each individual particle in the swarm is found using a fitness function called evaluation function.

The popular penalty function method employs functions to reduce the fitness of the particle in proportion to the magnitude of the constraint violation. The penalty parameters are chosen carefully to distinguish between feasible and infeasible solution [11].

The evaluation function is defined to minimize the non-smooth cost function for a given load demand while satisfying the constraints. The penalty function is given as shown in Equation 8.

$$F_T = \sum_{i=1}^{n} F_i(P_i) + \alpha\left[\sum_{i=1}^{n}(P_i) - (P_D + P_{Loss})\right]^2 + \beta\left[\sum_{k=1}^{n_i} P_i(violation)_k\right]^2 \qquad (8)$$

Where α is the parameter for not satisfying load demand and β represents the penalty for a unit loading falling within a prohibited operating zone penalty.

3.2 PSO Algorithm

PSO is used in this work for economic dispatch of power generation. PSO algorithm is described for an 'm' dimensional search space and 'n' population of particles, which encode solutions to the problem, moving in the search space in attempt to discover better solutions as follows:

1. Each particle has a position vector X_i and a velocity vector V_i. The position vector X_i and the velocity vector V_i of the i-th particle in the m-dimensional search space can be represented respectively as

$$X_i = (x_{i1}, x_{i2}, \ldots, x_{im}) \quad (9)$$

$$and\ Vi = (v_{i1}, v_{i2}, \ldots, v_{im}) \quad (10)$$

2. Each particle has a memory of the best position in the search space that it has found so far (*Pbest*$_i$), and knows the best location found to date by all the particles in the swarm (*Gbest*).

3. The initialization process starts with the generation of a fixed number of randomly generated particles (potential solutions) scattered in a multidimensional solution space. A swarm of birds (particles) moves around in a multidimensional search space (where the solution really exists) until they find the food (optimal solution).

4. Each particle in the swarm represents a candidate solution to the problem and moves towards the optimal point by appending a velocity to its position.

5. Using its own experience (*Pbest*) and the experience attained by the neighboring particles in the swarm (*Gbest*), each particle updates its position during its flight. In this way, each particle makes use of the *Pbest* and *Gbest*.

6. The update mode is termed as the velocity of particles. Particles update their positions and velocities in a heuristic manner. The velocity and the position of *i*th particle for fitness evaluation at (*k*+1) iteration in *m*-dimensional search space are computed by

$$V_{id}^{k+1} = wV_{id}^{k} + c_1r_1 * (Pbest_{id}^{k} - x_i^{k}) + c_2r_2 * (Gbest_d^{k} - x_i^{k}) \quad (11)$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (12)$$

$$v_i^{k=0} = 0, \quad i = 1, 2, \ldots, n, \quad d = 1, 2, \ldots, m.$$

Where:

i	particle's index
k	discrete time index/iteration count
d	dimension being considered
n	number of particles in the swarm
m	dimensions of a particle
V_{id}^{k}, x_{id}^{k}	velocity and position of particle i in dimension d at iteration k resp.
w	inertia weight factor
c_1,c_2	acceleration coefficient for the cognitive and social components resp.
r_1,r_2	uniform random numbers between 0 and 1
$Pbest_i^{k}$	best position found by *i*th particle at iteration k
$Gbest^{k}$	best position found by the entire swarm of particles at iteration k.

7. For this work, constriction coefficient in the PSO algorithm was employed.

8. To ensure balance between (global) exploration and (local) exploitation of a swarm, Clerc and Kennedy [12] in 2002 proposed another parameter named constriction factor *C*. The improved exploration-exploitation capabilities of PSO actually are translated into its enhanced convergence characteristics. The constriction factor is defined as follows:

$$C = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|} \quad (13)$$

where $\varphi = c_1 + c_2, \quad 4.1 \leq \varphi \leq 4.2;$ (14)

The velocity update formula now becomes

$$V_{id}^{k+1} = C[\, V_{id}^{k} + c_1r_1 * (Pbest_{id}^{k} - x_i^{k}) + c_2r_2 * (Gbest_d^{k} - x_i^{k})\,] \quad (15)$$

3.3 Data of Systems Employed for Optimal Dispatch

3.3.1 IEEE 30-Bus 6-Units Test System Data

The standard IEEE 30-bus 6-units test system data is used for the first simulation. The data of this test system was obtained from [13]. The PSO algorithm with constriction factor is used to develop the MATLAB codes. The parameters/characteristics of the generating units is initialized in a function which is called and used by the main PSO code while running. For cost function given by

$$\sum F_i(P_i) = \sum (a_i + b_iP_i + c_iP_i^2) \quad (16)$$

The generator characteristics are shown in Tables 2 and 3.

Table 2: Generating limits and fuel cost coefficient of IEEE 6-unit test system [13].

Unit	$P_i^{min}(MW)$	$P_i^{max}(MW)$	$a_i(\$/h)$	$b_i(\$/MWh)$	$c_i(\$/MW^2h)$
1	100	500	240	7.0	0.0070
2	50	200	200	10.0	0.0095
3	80	300	220	8.5	0.0090
4	50	150	200	11.0	0.0090
5	50	200	220	10.5	0.0080
6	50	120	190	12.0	0.0075

Table 3: Ramp rate limits and prohibited operating zones of six thermal generating units [13].

Unit	P_i^0	UR_i	DR_i	Prohibited Operating Zone	
				Zone1(MW)	Zone2(MW)
1	440	80	120	[210, 240]	[350, 380]
2	170	50	90	[90, 110]	[140, 160]
3	200	65	100	[150, 170]	[210, 240]
4	150	50	90	[80, 90]	[110, 120]
5	190	50	90	[90, 110]	[140, 150]
6	110	50	90	[75, 85]	[100, 105]

B-Coefficient Matrix:
B = [0.0017 0.0012 0.0007 -0.0001 -0.0005 -0.0002; 0.0012 0.0014 0.0009 0.0001 -.0006 -0.0001; 0.0007 0.0009 0.0031 0.0000 -0.0010 -0.0006; -0.0001 0.0001 0.0000 0.0024 -0.0006 -0.0008; -0.0005 -0.0006 -0.0010 -0.0006 0.0129 -0.0002; -0.0002 -0.0001 -.0006 -0.0008 -0.0002 0.0150]
B_0 = 1e-3*[-0.3908 -0.1279 0.7047 0.0591 0.2161 -0.6635];
B_{00} = 0.056;
The total system load demand was 1263 MW

3.3.2 Nigerian 28-Bus 10-Units System Data

The data and network parameters of the 28 bus 330kV Nigerian grid used for this research was obtained from [20]. Table 4 shows the bus number and bus name of the various buses shown on the one-line diagram of Figure 1. These bus numbers are unique to the respective buses they are assigned and will be used to identify them in the MATLAB programs. The PSO based ELD of the Nigerian 28-bus system is implemented for a total forecasted load demand of 2000MW.

To determine the loss coefficients or the B-coefficients (B_{ij}, B_0 and B_{00}) of the system, the bus data and line data of the network of interest in this case the 28 bus 330kV Nigerian grid is required as input to the MATLAB program. Table 5 below shows the bus data for the system, the first column contains the bus number which corresponds to the numbering in Table 4 and Figure 1. Column 2 contains the bus code used to identify the bus type where;

Table 4: Bus Numbers and Name of the 28 Buses on the Nigerian National Grid [14].

Bus No	Bus Name	Bus No	Bus Name
1	Egbin	15	Aiyede
2	Delta	16	Oshogbo
3	Kainji	17	Benin
4	Shiroro	18	Ajaokuta
5	Sapele	19	Akamgba

6	Jebba G.S.	20	Ikeja West
7	Afam	21	Onitsha
8	AES	22	New Heaven
9	Okpai	23	Alaoji
10	Calabar	24	Aladja
11	Gombe	25	Aja
12	Jebba T.S.	26	Birnin kebbi
13	Jos	27	Kaduna
14	Katampe	28	Kano

Bus code 1: is the Slack bus,
Bus code 2: is Generator bus or a PV bus,
Bus code 0: is load bus or a PQ bus.

Columns 3 and 4 are the voltage magnitude (in p.u) and angle (in degrees), respectively. Columns 5 and 6 are the real power (in MW) and reactive power (in Mvar) consumed by the load connected to the bus. Columns 7 and 8 contain the generated real and reactive power, respectively at the generator buses. Columns 9 and 10 shows the maximum and minimum reactive power output from the generators. Column 11 shows the reactive power injected into the system from compensating devices (capacitors and synchronous condensers) connected to the bus.

Table 5: Bus Data for 28 Bus 330kV Nigerian Grid [14].

Bus no.	**Bus Code**	**Voltage Mag. (in p.u)**	**Angle (in Degree)**	**Load MW**	**Load Mvar**	**Gen MW**	**Gen Mvar**	**Gen Q_{min}**	**Gen Q_{max}**	**Injected Mvar**
1	1	1	0	150	105.62	0	0	-200	200	0
2	2	1	0	200	300	882	0	-300	320	0
3	2	1	0	0	0	760	0	-210	222	0
4	2	1	0	0	0	600	0	-120	140	0
5	2	1	0	0	0	1020	0	-250	260	0
6	2	1	0	0	0	578	0	-200	210	0
7	2	1	0	0	0	931.6	0	-290	300	0
8	2	1	0	0	0	302	0	-100	110	0
9	2	1	0	0	0	480	0	-200	210	0
10	2	1	0	0	0	600	0	-120	140	0
11	0	1	0	0	0	0	0	0	0	0
12	0	1	0	130	80	0	0	0	0	0
13	0	1	0	220	154.8	0	0	0	0	0
14	0	1	0	114	90	0	0	0	0	0
15	0	1	0	110	80	0	0	0	0	0
16	0	1	0	104	70	0	0	0	0	0
17	0	1	0	36	25	0	0	0	0	0
18	0	1	0	72	45	0	0	0	0	0
19	0	1	0	136	84	0	0	0	0	0
20	0	1	0	72	45	0	0	0	0	0

21	0	1	0	39	27.8	0	0	0	0	0
22	0	1	0	84	50	0	0	0	0	0
23	0	1	0	146	84.5	0	0	0	0	0
24	0	1	0	32	17.8	0	0	0	0	0
25	0	1	0	110	80	0	0	0	0	0
26	0	1	0	100	58.4	0	0	0	0	0
27	0	1	0	80	49.6	0	0	0	0	0
28	0	1	0	26	15.3	0	0	0	0	0

The line data for the 28 Bus 330kV Nigerian grid is shown in Table 6. This is also one of the inputs to the bloss.m MATLAB program, line connections are identified by the mode-pair method. Table 5 contains the various interconnections between the buses and their respective line parameters and transformer tap setting (if any). The data in Table 6 has the following base values:
MVA Base = 100MVA
Base Voltage = 330kV.
Columns 1 and 2 are the line bus numbers. Columns 3 through 5 contain the line resistance(R), reactance(X) and half the total line charging susceptance all in p.u on an MVA Base of 100MVA. Column 5 is for the transformer tap setting. The lines may be entered in any sequence or order with the only restriction being that if the entry is a transformer, the left bus number is assumed to be the tap side (usually primary side) of the transformer.

Table 6: Line Data for the 28 Bus 330kV Nigerian Grid [14].

From Bus	To Bus	R(in p.u)	X(in p.u)	B/2 (in p.u)	tap setting
1	8	0.0001	0.0004	0.0498	1
1	20	0.0004	0.0029	0.0386	1
1	25	0.0007	0.0057	0.0386	1
3	17	0.0008	0.0063	0.1793	1
2	24	0.0008	0.0063	0.1793	1
3	26	0.0041	0.0304	0.9068	1
3	12	0.001	0.0082	0.462	1
4	27	0.0011	0.0097	0.273	1
4	12	0.0022	0.0234	0.6953	1
4	14	0.009	0.0067	0.8967	1
5	17	0.0002	0.0015	0.468	1
5	24	0.0008	0.0063	0.1793	1
6	12	0.0001	0.014	0.0498	1
7	23	0.0015	0.0027	0.156	1
9	21	0.0008	0.0063	0.1793	1
10	23	0.0163	0.014	0.393	1
11	13	0.0032	0.0027	0.7575	1
12	16	0.0019	0.0159	0.4478	1
13	27	0.0027	0.0202	0.6057	1
15	16	0.0013	0.01	0.2999	1

15	20	0.0016	0.0134	0.4029	1
16	17	0.003	0.0254	0.7155	1
16	20	0.0033	0.0227	0.741	1
17	18	0.0023	0.0198	0.5559	1
17	20	0.0034	0.0016	0.8508	1
17	21	0.0016	0.0139	0.3905	1
19	20	0.0007	0.0057	0.1928	1
21	22	0.0011	0.0097	0.2738	1
21	23	0.0163	0.014	0.393	1
22	23	0.0023	0.0171	0.6953	1
27	28	0.0027	0.0202	0.6057	1

The characteristics of any generator can be represented by the quadratic cost function given as:

$$C_i = \alpha_i + \beta_i P_i + \gamma_i P_i^2$$

(17)

Where: γ_i, β_i and $\alpha_{i,}$ are quadratic, linear and constant cost coefficients respectively of the ith generating unit. Equation 17 defines how much it will cost to generate a power of P (MW) from the ith generator. These coefficients can be obtained for both hydro and thermal generating units from the generator manufacturer's data sheet. Table 7 shows the values of these constants along with the maximum and minimum real power output of these generators.

Table 7: Available Generating Plant Characteristics of Nigerian 28-bus system [3]

Bus No.	Bus Name	α	β	Γ	P_min	P_max
1	Egbin	1278	13.1	0.031	275	1100
2	Delta	525.74	6.13	1.2	75	300
5	Sapele	6929	7.84	0.13	137.5	550
7	Afam	1998	56	0.0092	135	540

These coefficients for the other generating stations connected to bus 3, 4, 6, 8, 9 and 10 of the Nigerian 28-bus power system could not be obtained due to certain limiting factors beyond our control during the course of this work, therefore approximate values were estimated. Table 8 shows the approximate estimated generating plant characteristics.

Table 8: Approximate Estimated Generating Plant Characteristics.

Bus No.	Bus Name	α	β	Γ	P_min	P_max
3	Kainji	15200	12	0.05	50	500
4	Shiroro	8200	17.1	0.027	50	450
6	Jebba	2100	9.5	0.22	100	400
8	AES	3886	22	0.453	135	540
9	Okpai	480.58	10.3	1.13	150	600
10	Calabar	2732	38.7	0.05	100	350

The B-Coefficients for this Nigerian 28-bus system is obtained by executing the b_loss.m script with the system bus data and line data shown Tables 5 and 6, respectively as inputs. The b_loss.m script file is part of the script files and functions developed by Hadi Saadat in his power system matlab toolbox-‘power’ [15]. The bloss.m works together the other script files such as ‘ifybus.m’ to determine the B-loss-coefficient for any system.

3.4 Development of The MATLAB Programs for the PSO

The MATLAB codes for the GUI simulation of PSO converging at global minimum of some well-known mathematical functions were obtained from PSO GUI toolbox developed by S. Samuel Chen in [16]. The MATLAB codes used in this work for optimal dispatching of generators were obtained from S. M. K. Heris [17].

IV. RESULTS

4.1 Results for GUI Demonstration of PSO

This section shows the various three-dimensional (3-D) functions employed for the GUI demo of PSO. The particles are shown (blue dots) initially randomly distributed in the search space of the functions at the first iteration; then the plots of the particle and functions, at selected iterations, is shown as the particles all converge to the global minimum of the test-function under consideration. The PSO GUI tool-box is a very useful tool for a good under-standing and visualization of the PSO working mechanism.

PSO GUI demo for the test function given by fitnessfcn:

Fitnessfcn1 = 3*(1-x1)2*exp(-(x12) - (x2+1)2)-10*(x1/5 – x13 – x25)*exp(-x12-x22)-1/3*exp(-(x1+1)2– x22) (18)

The test function named fitnessfcn is a function in ‘x’ of two independent variables x1 and x2. This test function has a local-minima and a global minimum point. It can be observed that as the particles converge to the optimum solution the plot of scores vs iteration/generation at the left-hand side becomes fairly constant. The score is constant from the 45th iteration to the 50th iteration. This value -6.55 is the global minimum. This test function shows how PSO carefully doesn’t trap at local minimum point, but instead always converges at global minimum.

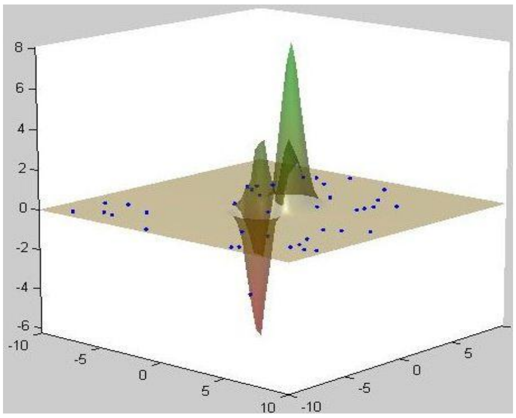

Figure 3. PSO GUI demo result for fitnessfcn first iteration

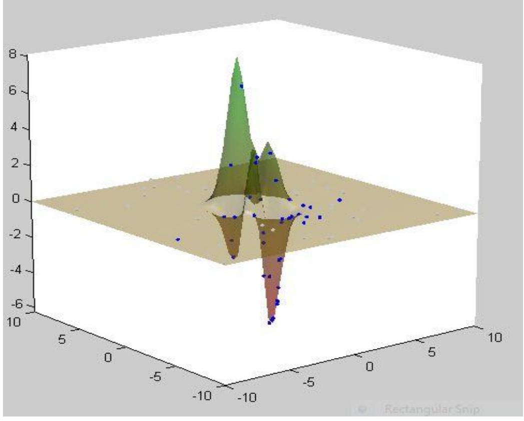

Figure 4. PSO GUI demo result for fitnessfcn 10 iteration

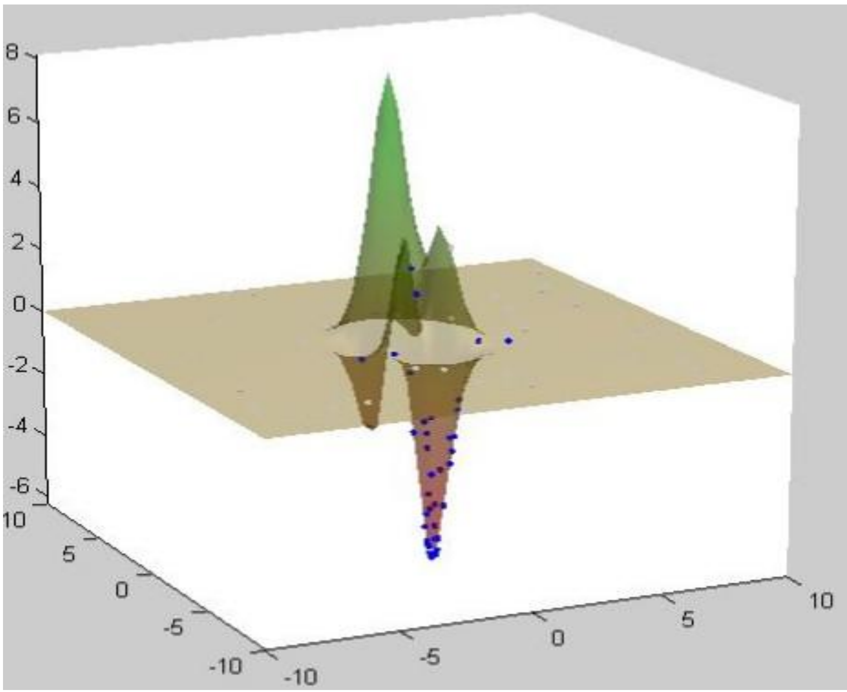

Figure 5. PSO GUI demo result for fitnessfcn after 20 iterations

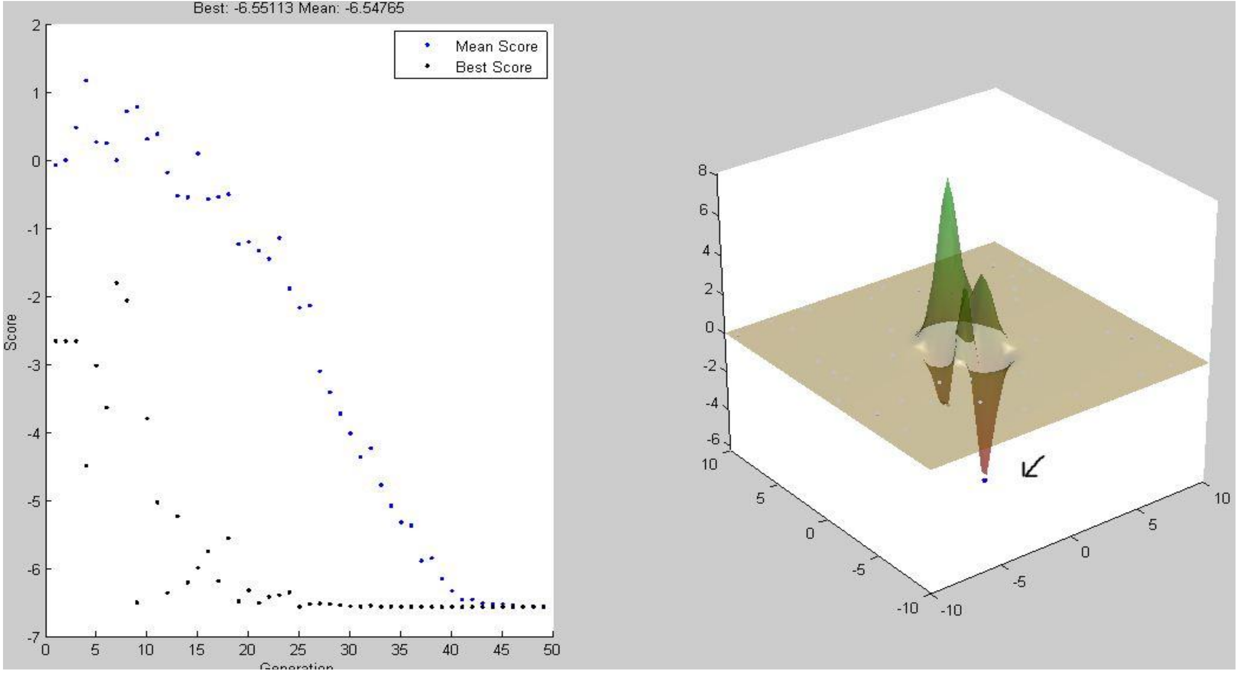

Figure 6. PSO GUI demo result for fitnessfcn after 50 iterations

4.2 PSO GUI Demo Results for dejongsfcn

The PSO GUI results obtained for different iterations are shown in Figures 7 – 9. It can be observed from the left-hand side graph of the plot in Fig. 9 for score vs iteration/generation that the optimum score becomes fairly constant from iteration 40 to 50. After the 50th iteration all the particles have converged at the minimum point. The best score and the mean score of the particles is shown at the top of the left-hand side graph as Best:1.40236e.09 and Mean: 6.2023e.05

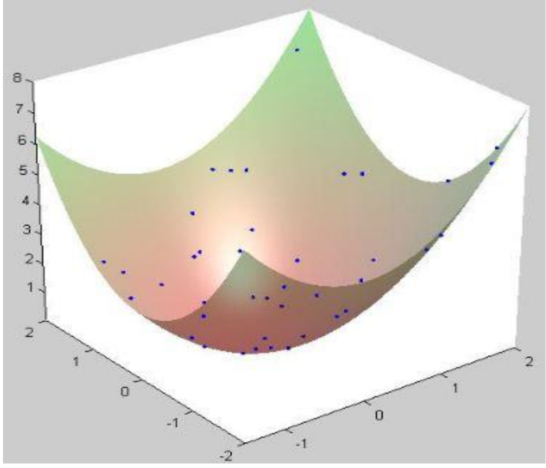

Figure 7. PSO GUI demo result for djongsfcn at 1st iteration

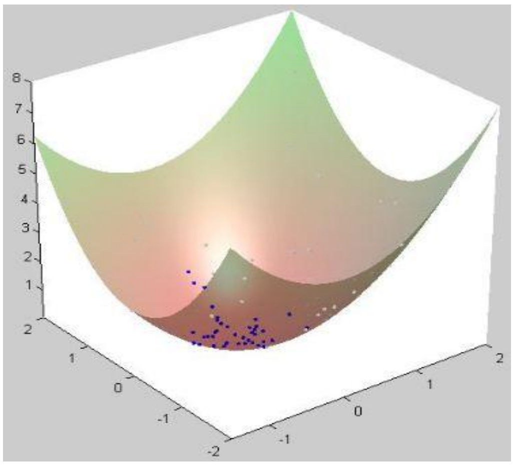

Figure 8. PSO GUI demo result for djongsfcn after 10 iterations

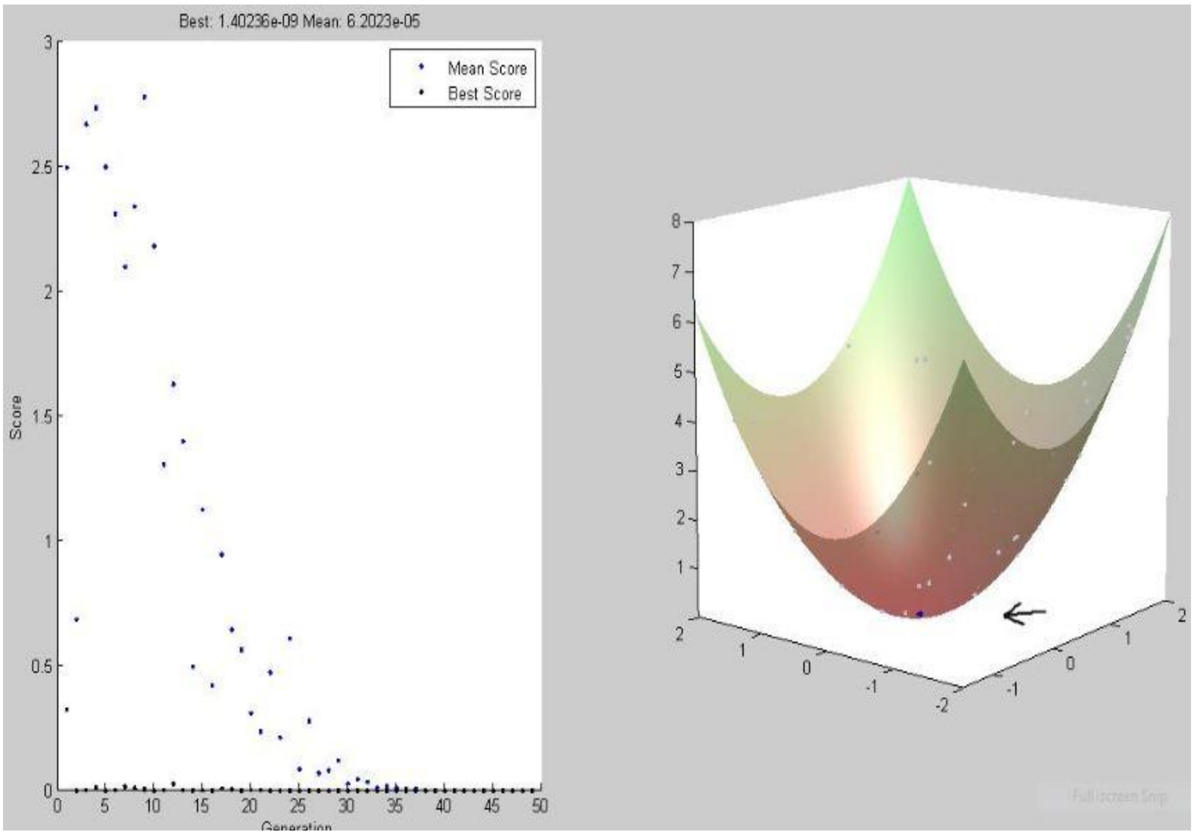

Figure 9. PSO GUI demo result for djongsfcn after 50 iterations

4.3 Results for IEEE 6-Unit Test System

Economic load dispatch is performed using PSO algorithm in MATLAB for the IEEE 6-unit test system data shown in Section 3.5.1. Optimal dispatch for this system is performed for a total load demand of 1263MW. The PSO algorithm is initialized with a population of 100 particles, and set to stop after 500 iterations. After 500 iterations the algorithm finds the optimum solution with very little error. The results shown in Figs 10 and 11 were obtained.

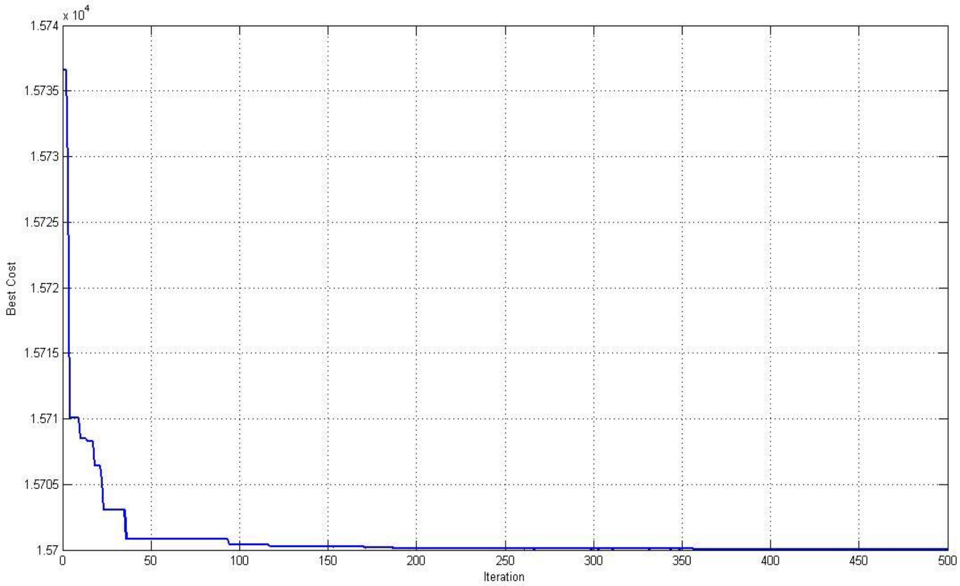

Figure 10: Plot of Best cost against the iterations for IEEE 6-unit system.

From the plot in Fig.10, Optimum/best total cost obtained = 15700.0929 N/hr. The program took a total run-time of 31.637 s

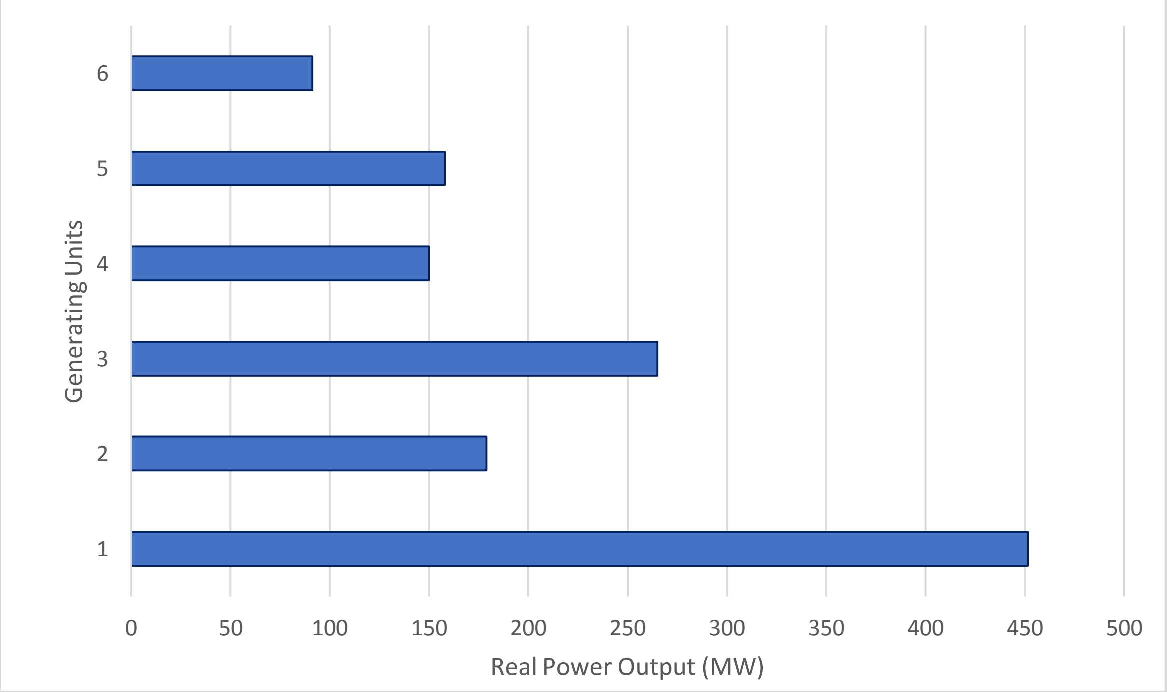

Figure 11. Bar chart representation of the units and corresponding real power output obtained for ELD of IEEE 6-unit test system.

4.4 Results for The Nigerian 28-Bus System

Total load demand used in this work was 2000 MW. PSO is initialized with 300 particles. The maximum number of iterations was set to 600. The results shown in Figs 12, 13 and Table 9 were obtained.

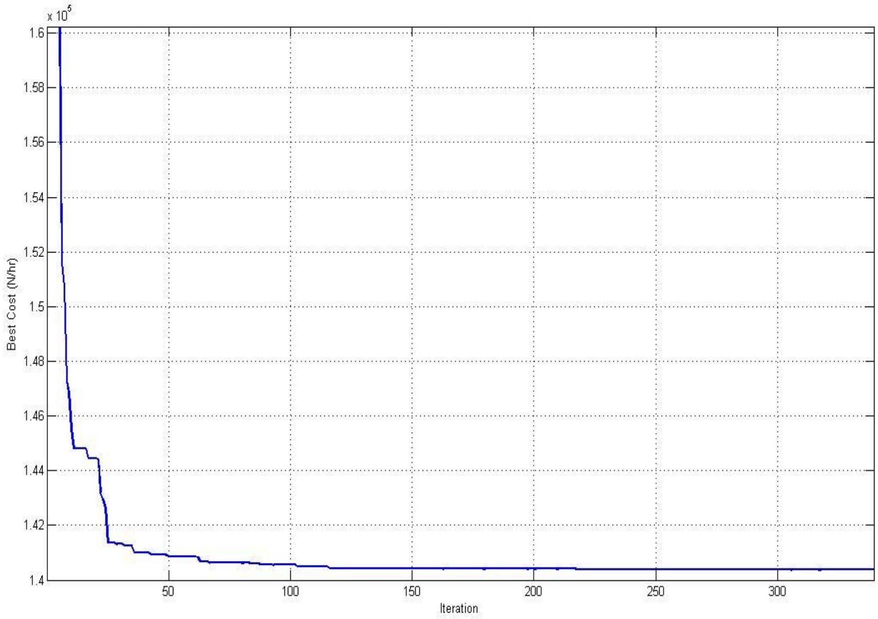

Figure 12: Plot of the Best Cost obtained in each iteration vs iteration for the 28-bus system

Optimum/Best Total Cost obtained = 140,373.4162 N/hr while the program took a total run-time of 75.514 s

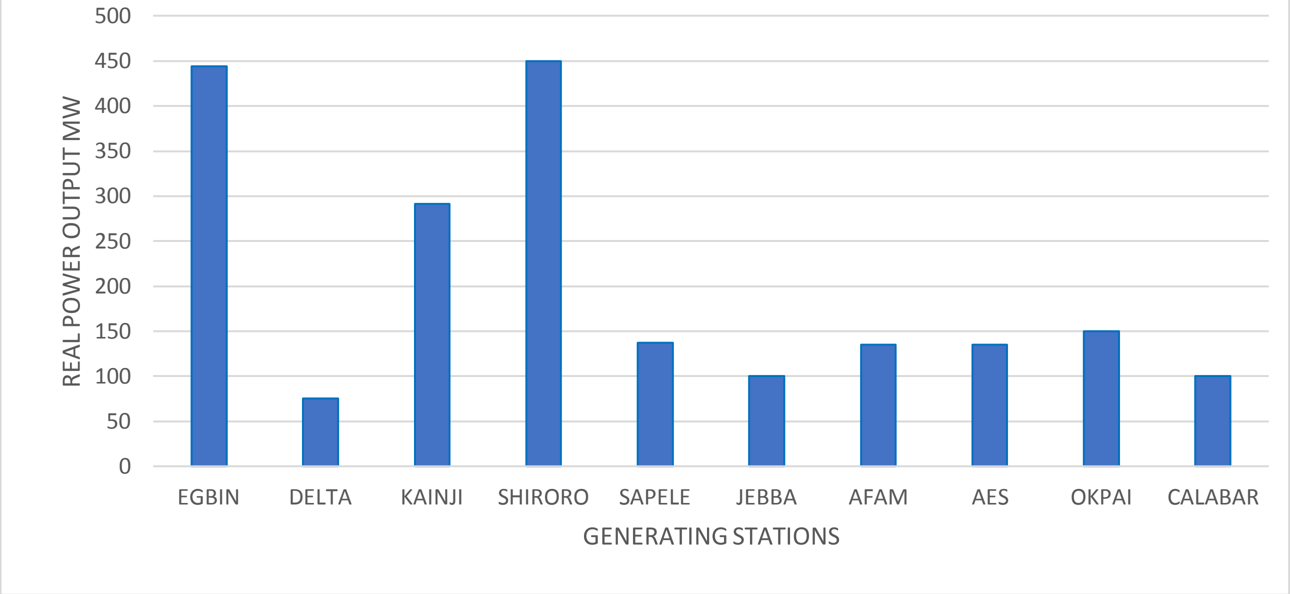

Figure 13: Bar chart representation of the units and corresponding real power output obtained for ELD of Nigerian 28-bus System.

Table 9: Units in the 28-bus system and corresponding optimal power output obtained.

S/N	Generating Stations	Power Output (MW)
1	EGBIN	444.4868
2	DELTA	75
3	KAINJI	291.5441
4	SHIRORO	449.9133
5	SAPELE	137.5
6	JEBBA	100.0004
7	AFAM	135.0017

8	AES	135
9	OKPAI	150
10	CALABAR	100.0015

4.5 Results Validation/Comparison with Referenced Work on Nigerian 30-Bus System

Optimal ELD is performed for the Nigerian 30-bus system using the data obtained from [18]. Total load demand of 2890 MW and total system power loss of 1.1836 MW was used as obtained from [18]. PSO was initialized with 200 particles and the maximum number of iterations is set to 500. The results shown in Figs 14 – 16 and Table 10 were obtained and compared with the result obtained in [18].

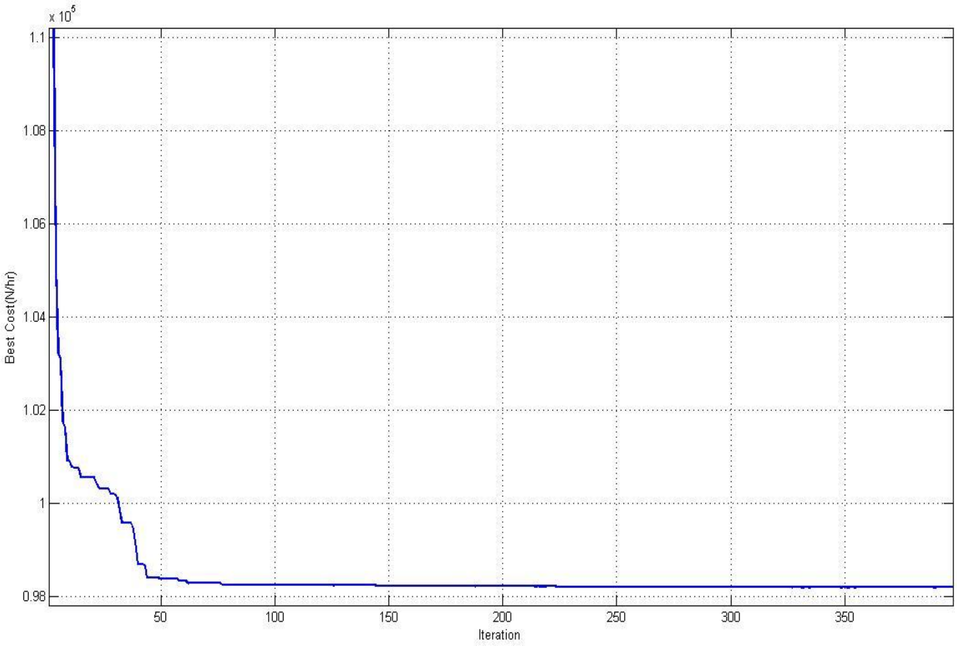

Figure 14: Plot of the Best Cost obtained in each iteration vs iteration for the 30-bus system.

Optimum/Best Cost obtained = 98197.1750 N/hr and the program took a total run-time of 40.440 s

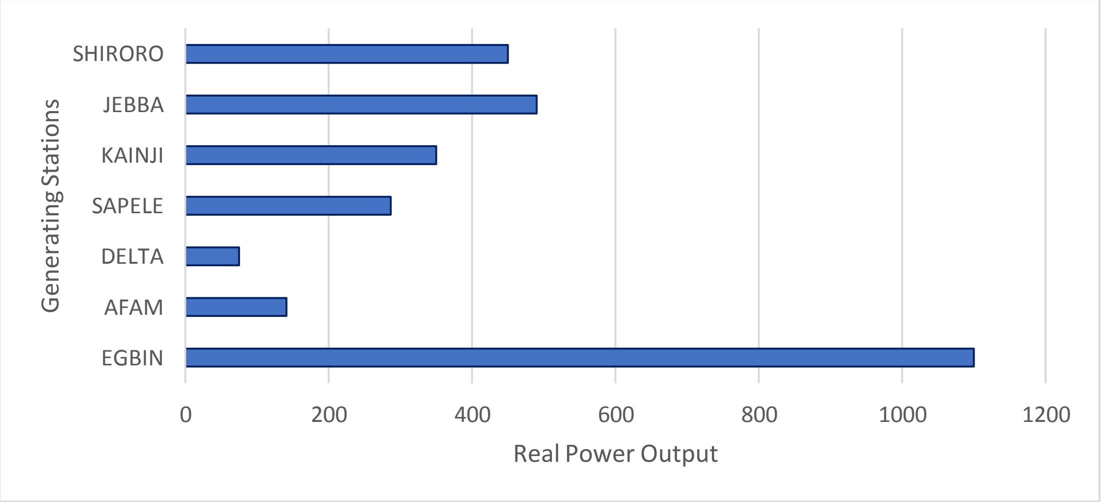

Figure 15: Bar chart representation of the units and corresponding real power output obtained for ELD of Nigerian 30-bus system.

The percentage difference between the optimum cost obtained in this work and that obtained in [18] is 2.7229%. This gives a low margin of error.

Table 10: Comparison of results obtained in this work with that obtained in [18].

Generating Stations/Data	Optimal Results obtained in this work	Optimal Results obtained in [18] referenced work.
Egbin P_g (MW)	1099.1965	1036.17
Afam P_g (MW)	140.5144	215.16
Delta P_g (MW)	75.0000	75.00
Sapele P_g (MW)	286.4744	274.99
Kainji P_g (MW)	350.0000	349.93
Jebba P_g (MW)	490.0000	489.99
Shiroro P_g (MW)	450.0000	449.87
Total power generated P_{g_total} (MW)	2891.1854	2891.11
Total Optimum Cost N/hr	98197.1750	100871.00

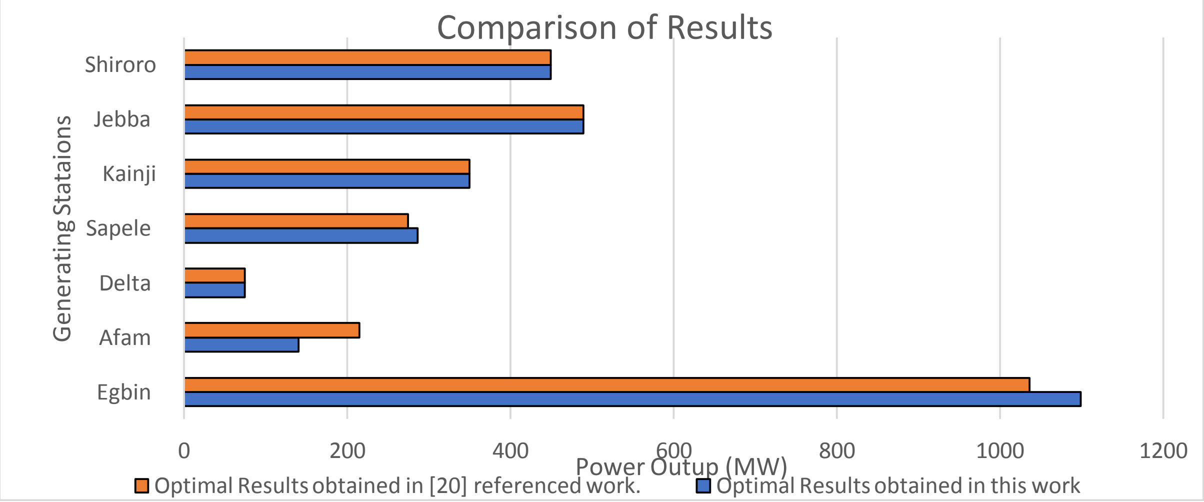

Figure 16: Graphical comparison of Optimal power output of each generating station obtained in this work and that obtained in referenced work.

V. DISCUSSION OF THE RESULTS

From the PSO GUI demonstrations in Section 4.1., it was observed that PSO is a very accurate algorithm with a fast convergence time and does not trap at local minima of functions with multiple minimum points.

Analyzing the results obtained for economic load dispatch in Section 4.2 through Section 4.5, the power system operator can make the following inferences:

i. As the load demand (P_d) on the system increases, the cost of generation increases. This is anticipated as the cost of power generation given by Equation 1, is directly dependent on the amount of power generated P_i, and P_i increases with P_d so does the fuel cost.

ii. The power loss in the system increases as load demand increases. Increase in load necessitates increase in generation, and power loss in the system depends on the power output as shown by the kron's loss formula in Equation 5. As more power is generated to meet the increase in demand the system is subjected to more stress causing more losses.

iii. Power output is allotted to the plants according to how economic they are. How economic it is to operate a generating plant is determined by a number of factors which includes: the plant fuel cost input-output characteristics, the minimum and maximum power output capacity, the B-loss coefficients and the location of the plant in the network.

iv. The more economic generators are allocated more power output are shown in Figures 11, 13, 15 and 16. In Figure 11, the most economic generator unit is Unit-1; in Figure 13 the most economic plant is Shiroro; while in Figure 15 the most economic plant is Egbin. Much share of the load demand is supplied by these units. These economic generators are usually operated for most of the time to take care of the base load on the network.

v. The most uneconomic units are allotted the least portion of the load. In Figure 11 the most uneconomic generator unit is Unit-6; in Figure 13 the most uneconomic plant is Delta; while in Figure 15 the most uneconomic plant is Delta. The uneconomic plants are usually only operated during peak load periods, they are generally called peak load generators.

vi. As the test-system network increased, the computation time of the algorithm increases.

A comparison of the result obtained in this work for the Nigerian 30-bus system and that obtained in [18] clearly shows that the PSO algorithm used in this work is reliable and even better. Better in the sense that a lower cost of operation was obtained while still satisfying the constraints.

VI. CONCLUSION

The working mechanism of PSO was successfully demonstrated with the aid of the PSO graphical user interface (GUI) toolbox in MATLAB. The PSO GUI demonstrations/simulations in Section 4.1 provides a very good visualization of the particles' movement in the search space while looking for the optimum solution. The GUI simulations clearly proves that PSO is a very accurate algorithm with a very fast convergence time. PSO algorithm is seen to be a very intelligent algorithm that is not cursed with the problem of trapping at local minima of functions with multiple minimum points, but instead always finds the global optimum efficiently.

PSO was successfully employed for the economic load dispatch of the IEEE 6-unit test system, the Nigerian 28-bus 10-units and the Nigerian 30-bus 7-units systems. In performing economic load dispatch, the PSO algorithm showed its effectiveness in managing constraints. The constraint management capability of the algorithm depends on the commands in the codes that tell the algorithm how to identify and manage the various constraints. It also depends on the capability of the software/platform used to develop the codes for the PSO algorithm.

A comparison of the results obtained in this work for ELD of Nigerian 30-bus system and the result obtained in [18] for same system data clearly shows that the algorithm used in this work is correct and even better.

Economic load dispatch is an important power system operation that is performed in real time. This algorithm and the MATLAB codes can be deployed by the power system operators to aid in their day-to-day operations.

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