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Particles Swarm Optimization Based Economic Load Dispatch of Nigeria Hydrothermal Considering Hydro Cost Functions

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Abstract:
This paper presents an optimization of Economic Load Dispatch (ELD) problem on the Nigeria national hydrothermal electric power system. Particle Swarm Optimization (PSO) Algorithm is then used to search for solution to a realistically formulated ELD problem. The results obtained are compared with published results of similar work obtained using Conventional Genetic Algorithm and Differential Evolution methods. The results revealed that, PSO algorithm gave the least production cost for all the cases considered and hence a better approach to the optimization of ELD for a hydrothermal system.

Keywords: PSO, ELD, Hydrothermal.

1. INTRODUCTION

Electrical power generation, transmission and distribution are the three stages of delivering electricity to consumers at residential, industry, commercial, and administrative areas. The supply of adequate and stable electricity to consumers is the back born of socioeconomic development of any nation. While inadequate and unstable supply of electricity to consumers in any nation would definitely lead that nation backward in terms its socio-economic growth. Like any other economic sector in Nigeria, the power sector has its peculiar problems. In fact the sector has multidimensional problems. Looking at the trend of electrical power system from inception starting from little utility networks, the use of electricity has grown bigger. Now, electric power systems became widespread and complex in nature. From its inception to present, power system utilization has pass through different stages. Generating stations are not at equal distance from each other or having equal fuel cost functions. Therefore to provide cheaper power, load has to be distributed among the various generating stations in order to minimize the cost of generation [1,6]. Electric power utilities is aimed to providing better quality and reliable power to consumers at a cheaper cost while meeting the operating limits of generators and satisfying its constraints.

This formulates the economic load dispatch problem for determining the optimal combination of the power output of all the online generators which minimizes the total fuel cost [2]. Classical algorithms like gradient method, lambda iteration and Newton method would have solve economic load dispatch problems if the fuel-cost curves of the generating units are piece-wise linear and monotonically increasing. But in reality the input-output characteristics of the generating units are non-smooth, non-linear, and discrete in nature resulting to prohibited operating zones, ramp rate limits and multi fuel effects [3]. Thus the resultant ELD becomes a challenging non-convex optimization problem, which is difficult to solve using the classical methods [4]. Cost function coefficients are computed for the hydro units using hydrological data obtained from the power system operator. Thermal cost functions are also obtained from system operator.

1.2 The Nigeria Hydrothermal Power System

For over twenty years prior to 1999, the power sector did not witness substantial investment in infrastructural development. During that period, new plants were not constructed and the existing ones were not properly maintained, bringing the power sector to a deplorable state. In 2001, generation went down from the installed capacity of about 5,600MW to an average of about 1,750MW, as compared to a load demand of 6,000MW. Also, only nineteen out of the seventy-nine installed generating units were in operation [10]. The electrical power demand in Nigeria is more than what is generated in the country with the availability of all the natural resources in the country. This is one of the reasons why the country's development is stunted and epileptic in nature which prolongs her development and risks losing potential investors. Constant power supply is the hallmark of a developed economy. Constant and reliable production of power is critical to the profitability of electricity utilities. This can only be realized when the power generators are scheduled efficiently to meet electricity demand. The main factors to be considered for the economic operation of the system are efficiency of generating unit, the transmission loses and the operating costs. Economic load dispatch has been applied to obtain optimal fuel cost to the systems while satisfying their constraints. In recent years, the Power Holding Company of Nigeria (PHCN) has been experiencing serious problem in generation, transmission, distribution, maintenance, financial constraints and increase in power demand, considering the generation/power demand problems, several units were on emergency/forced outages, which led to system disturbance such as; partial and total system collapse. These problems were attributed to over stressing the units to generate outside their normal operating conditions [10, 11]. This will thus lead to generating electric power at loss. With regards to these problems, it is required to study the cost functions of the available thermal units, the country's maximum power demand, and the power limits in order to carry out the economic load dispatch problem. The current installed capacity of grid electricity is about 6000MW, of which about 67 percent is thermal (Afam, Egbin, Sapele, Delta,) and the balance is hydro-based (Kainji, Shiroro, Jebba). Between 1990 and 1999, there was no new power plant built and the same period witnessed substantial government underfunding of the utility for both capital projects and routine maintenance operations. Generating plant availability is low and the demand – supply gap is crippling. Poor services have forced most industrial customers to install their own power generators, at high costs to themselves and the Nigerian economy [10]. The aim of this paper is to apply a particle swarm optimization technique to solve the economic load dispatch (ELD) problem of Nigeria thermal power plants for optimal allocation of the total power demand among the available generating units so as to minimize the total generation cost subject to system constraints.

1.2.1 Need of Hydrothermal Scheduling

The operating cost of thermal plant is very high, though their capital cost is low. On the other hand the operating cost of hydroelectric plant is low, though their capital cost is high [14]. So it has become economical to have both thermal and hydro plants in the same grid. The hydroelectric plant can be started quickly and it has higher reliability and greater speed of response. Hence hydroelectric plant can take up fluctuating loads.

1.3 Problem Formulation

The formulation of the ELD has appeared in many literature such as [1, 3, 4]. This is briefly reviewed in what follows. Consider a system consisting of n-thermal and hydro generating units connected to a transmission network as shown in figure 1 below.

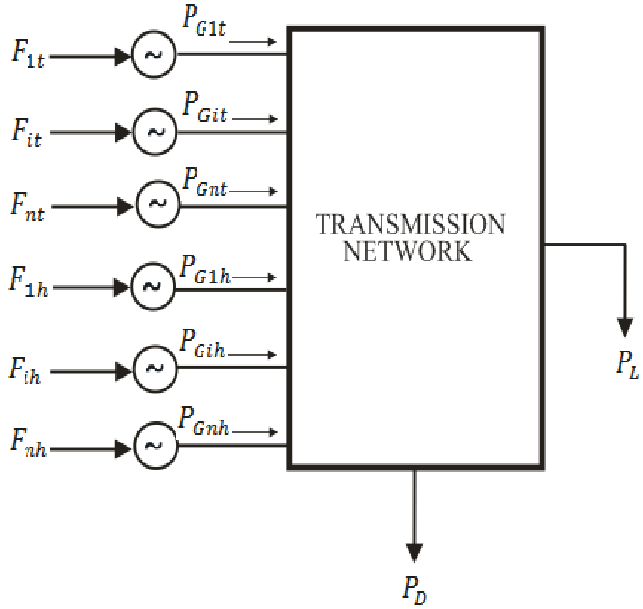

Figure.1. interconnected power system network

Where;

F_{it} is the fuel cost of thermal unit *i*

P_{Git} is the power delivered by thermal unit *i*

F_{ih} is the fuel cost of hydro unit *i*

P_{Gih} is the power delivered by hydro unit *i*

P_L is the total power loss

P_D is the total power demand

Very often the cost functions are in quadratic form given by

$$F_i(P_{Gi}) = \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \quad (1)$$

Where;

α_i is the constant cost coefficient of unit i

β_i is the linear cost coefficient of unit i

γ_i is the quadratic cost coefficient of unit i

The economic load dispatch is aimed at minimizing the total fuel cost of power system subject to generation constraints. This can be expressed as

$$F_T = \sum_{i=1}^{n} F_i(P_{Gi}) \quad (2)$$

Where

F_T is the total cost of power generation

$F_i P_{Gi}$ is the generation cost of unit *i*

The minimization of (2) is further subject to the following equality and inequality constraints.

A lot of stochastic meta heuristic approaches such as particle swarm optimization (PSO), evolutionary programming (EP), differential evolution (DE), genetic algorithm (GA), artificial neural network (ANN), simulated annealing (SA), ant colony (ACS), tabu search (TS), firefly algorithm (FA), Cuckoo Search (CS) etc have been developed for solving both linear and non-linear economic load dispatch problems [6-10].

Some researchers that have applied the heuristic approaches to solve ELD problems are briefly reviewed in what follows:

[1] (Puri et al, 2016) Shows how the formation of Economic Load dispatch (ELD) problem plays a significant role in the functioning of electrical power systems. It is used in determining the optimal cost for satisfying the demand with available electric generation resources. The ELD problem of thermal units results in significant saving for electrical utilities.

[3] (Kaur and Kuamr, 2014) discussed the planning of power output for each devoted generator unit in such a way that the operating cost is minimized and simultaneously matching load demand, power operating limits and maintaining stability as the problem of economic dispatch in power system. This problem becomes more complex in large scale power systems as it is hard to find out optimal solution because it is non linear function and it contains number of local optimal.

[4] (Nema and Gajbhiye, 2014) describe and Introduce a new nature Inspired Artificial Intelligence method called Firefly Algorithm(FA) as a stochastic Meta heuristic approach based on the idealized behavior of the flashing characteristics of fireflies. The aim is to minimize the generating unit's combined fuel cost having quadratic cost characteristics subjected to limits on generator real power output & transmission losses. The paper presents an application of the FA to ED with valve point loading for different Test Case system and the solution looks promising to GA.

[15] (Pham et al., 2016) Present the use of an enhanced version of conventional cuckoo search algorithm for solving optimal generation coordination of hydrothermal system where the objective is to minimize both fuel cost and emission, and the hydro model is represented as a quadratic function of water discharge with respect to generation.

In this paper, particle swarm optimization (PSO) algorithm is proposed to solve the ELD problems in the Nigeria hydroelectric power systems. The viability of the method is analyzed for its accuracy and rate of convergence on the Nigerian power network (1999 model) and results were compared with other heuristics methods.

(a) Equality Constraints

The total power generation from thermal and hydro units must satisfy the load demand and power losses in transmission lines represented by:

$$\sum_{i=1}^{N_1} P_{Git} + \sum_{i=1}^{N_2} P_{Gih} - P_L - P_D = 0 \quad (3)$$

Where

P_{Git} is power output of thermal unit *i*

P_{Gih} is power output of hydro unit *i*

P_D and P_L are total system load demand and total transmission loss respectively; and

B_{ij}, B_{oi}, B_{oo} are matrix coefficients for transmission power losses.

The power losses P_L in the transmission lines are calculated using Kron's formula as follows:

$$P_L = \sum_{i=1}^{N_1+N_2} \sum_{j=1}^{N_1+N_2} P_i B_{ij} P_j + \sum_{i=1}^{N_1+N_2} B_{0i} P_i + B_{OO} \quad (4)$$

Using the B – coefficient method, network losses are expressed as:

$$P_L = P_{Gi}^T B P_{Gi} \quad (5)$$

Where B is the loss coefficient

(b) Inequality constraints

For all units, thermal and hydro,

$$P_{Gi}^{min} \le P_{Gi} \ge P_{Gi}^{max} \quad (6)$$

Where

P_{Gi}^{min} is the minimum power limit of unit *i*

P_{Gi}^{max} is the maximum power limit of unit *i*

(c) Water Availability Constraints

Hydro units have a water availability constraint which is used in the determination of the hydro cost function.

1.4 Particle Swarm Optimization

Particle swarm optimization (PSO) is the tool chosen as a technique for the actualization of this work. Russel Ebenhart (Electrical Enineer) and James Kennedy (Social Psychologist) in 1995, developed out of attempts to model bird flocks and fish schools Inspired by the social behavior of birds, studied by Craig Reynolds (a biologist) in late 80s and early 90s develops particle swarm optimization [12]. This was later used in computer simulations of virtual birds recognized for suitability technique for optimization. PSO simulates the behaviours of bird flocking. Suppose the following scenario: a group of birds are randomly searching food in an area. There is only one piece of food in the area being searched. All the birds do not know where the food is. But they know how far the food is in each iteration. So what's the best strategy to find the food? The effective one is to follow the bird, which is nearest to the food. PSO learned from the scenario and used it to solve the optimization problems.[6] In PSO, each single solution is a "bird" in the search space. We call it "particle". All of particles have fitness values, which are evaluated by the fitness function to be optimized, and have velocities, which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles. PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. Particle swarm optimization has been found to be extremely effective in solving a wide range of engineering problems and solves them very quickly.

1.5 Methodology

1.5.1 Computation of quadratic cost function of hydro units

The total water discharge for each hydro unit during the scheduled period is limited by the availability amount of water for that unit as follows:

$$\sum_{m=1}^{M} t_m q_{i,m} = W_i \; ; \; i = 1, \ldots, N_2 \quad (7)$$

Where $q_{i,m}$ is the rate of water flow via turbine of hydro *i* in interval *m*

$$q_{i,m} = a_{ih} + b_{ih} P_{hi,m} + c_i P_{ih,m}^2 \; m^3/s \quad (8)$$

where a_{ih}, b_{ih}, c_{ih} are water discharge coefficients of hydro units *i* and W_i is the volume of water available for generation by hydro plant *i* during the scheduled period.

The hydro generation is obtained as

$$P_{hj,m} = \frac{-b_{ih} \pm \sqrt{b_{ih}^2 - 4c_{ih}(a_{ih-} q_{i,m})}}{2C_{hj}} \; ; m = 1,\ldots M; \; i = 1,\ldots N_2 \quad (9)$$

$$\text{Where } [b_{ih}^2 - 4c_{ih}(a_{ih-} q_{i,m})] \ge 0 \quad (10)$$

The hydro unit operating range is [16]

$$q = c_{ih} + b_{ih}(P_H - 342.63) + a_{ih}(P_H - 342.63)^2 \; m^3/h \quad (11)$$

$200 < P_H < 700$ MW

The aim of this research is to distribute the total power demand among the available thermal and hydro generating stations to minimizing the total fuel cost subject to both equality and inequality constraints as earlier stated (1) - (3) and Particle Swarm Optimization is used to achieve this desired goal.

1.5.2 PSO Optimization

The term PARTICLE refers to a member of population which is mass less and volume less *m* dimensional quantity. It can fly from one position to other in *m* dimensional search space with a velocity. For example in ELD problem of 3 machine systems each particle will have 3 dimensions representing generation of each machine. In real number space, each individual possible solution can be represented as a particle that moves through the problem space. Therefore, let *p* and *v* denotes a particle's coordinate (position) and its corresponding flight speed (velocity) in a search space, respectively. Therefore, the j^{th} particle is represented as $P_i = [P_{i1}, P_{i2}, P_{i3}, \ldots, P_{iNG}]$ in the NP dimensional space. The best previous position of each particle is recorded and represented as $Pb_i = [Pb_{i1}, Pb_{i2}, Pb_{i3}, \ldots, Pb_{iNG}]$. The index of best particle among all the particles in the group is represented by the $[G_1, G_2, G_3, \ldots, G_{NG}]$. The velocity of the particle is represented as $V = [V_{i1}, V_{i2}, V_{i3}, \ldots, V_{iNP}]$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from Pbij to Gj as shown in the following formulas [14].

$$v_{ij}^{r+1} = wv_{ij}^r + C_1R_1 (pb_{ij}^r - p_{ij}^r) + C_2R_2 (G_j^r - p_{ij}^r) \; (i = 1, 2, \ldots, NP; \; j = 1, 2, \ldots, NG) \quad (12)$$

$$p_{ij}^{r+1} = p_{ij}^r + v_{ij}^r - p_{ij}^{r+1} \; (i = 1,2,3, \ldots, NP; \; j = 1, 2, \ldots, NG) \quad (13)$$

Where

NP is the number of individual particles (generators within a station)

NG is the number of generating units being evaluated

C_1 and C_2 are the acceleration constants

R_1 and R_2 are uniform random values in range (0.1)

v_{ij}^r is the velocity of j^{th} member of i^{th} particle at r^{th} iteration, $v_j^{min} \leq v_{ij}^r \leq v_j^{max}$

P_{ij}^r is the current position of j^{th} member of i^{th} particle at r^{th} iteration. In the above procedure, the parameter v_j^{min} determined the resolution, or fitness with which regions are to be searched between the present position and the target position. If v_j^{max} is too high, particles might fly past good solutions. If v_j^{max} is too small, particle may not explore sufficiently beyond local solutions. In many experiences with PSO, v_j^{max} was often set at (10 – 20)% of the dynamic range of the variable on the variable of each dimension. The constant C_1 and C_2 rep resents the weighting of the stochastic acceleration term that put each particle towards the pb_{ij}^r, G_j^r positions. Low values allow particles to roam far from the target region before being tugged back. On the other hand, high value results in abrupt movement towards or past target regions. Hence, the acceleration constants C_1 and C_2 were often set to be 2.0 according to past experiences [13]. The above equations are written as

$$v_{ij}^{new} = wv_{ij} + C_1R_1(p_{ij}^{best} - p_{ij}) + C_2R_2(G_j^{best} - p_{ij})\ (i = 1, 2,..,NP;\ j = 1, 2,..,NG) \quad (14)$$

$$p_{ij}^{new} = p_{ij} + v_{ij}^{new}\ (i = 1, 2,...,NP;\ j = 1, 2,.....,NG) \quad (15)$$

In the strategy of PSO, the particles best position p_{ij}^{best} and the global best position G_j^{best} are the key factors. The best position out of all p_{ij}^{best} is taken as G_j^{best}. Suitable selection of inertia weight in equation below provides balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. As originally developed, *w* often decrease linearly about 0.9 to 0.4 during a run. In general inertia weight *w* is set according to (16) and is used in (14)

$$W = W_{\max} - \frac{W\max - W\min}{ITER\max} \text{ x } ITER \quad (16)$$

Where

W is the inertia weight factor

$ITER_{\max}$ is the maximum number of iterations (generation) and

ITER is the current number of iterations. Eqation (14) is used to calculate the particle's new velocity according to its previous velocity and the distances of its current position from its own best experience (position) and the group's best experience. Then the particle flies towards a new position according to (15). The performance of each particle is measured according to a predefined fitness function, which is related to the problem to be solved. The main objective of economic dispatch is to obtain the amount of real power to be generated by each committed generator, while achieving a minimum generation cost within the constraints. The particle swarm optimization is implemented by searching the generation of power plants, p_i within generator limits. This section provides the solution methodology to the economic dispatch problems using PSO. The evaluation function for evaluating the minimum generation cost of each individual in the population is adopted as follows:

$$F_T = \sum_{i=1}^{n} F_i(P_{Gi}) \quad (17)$$

The Steps of implementation

Step 1: Initialize swarm size

The population is initialized randomly within the restrictive maximum and minimum limits for each of the generating units such that whole of the population thus formed must be satisfying all the constraints.

Step 2: Evaluate Fitness

Initialize the relevant PSO parameters, population size, C1, C2, maximum and minimum inertial weight, maximum and minimum velocity limit, etc. Calculate fitness i.e Pbest (the best value it had obtained so far) and set this fitness equal to local fitness and assign the corresponding positions as local best position

Step3: Compare particle's fitness analysis with particle's pbest;

If the current price is best than pbest, then set pbest price adequate to the present price, and also the pbest location adequate to the present location in the d-dimensional area.

Step4: Compare fitness analysis with the population's overall previous best;

If the current price is best than gbest, then reset gbest to the present particles array index and price.

Step5: amendment the speed of the particle in keeping with equation (14)

$$v_{ij}^{new} = wv_{ij} + C_1R_1(p_{ij}^{best} - p_{ij}) + C_2R_2(G_j^{best} - p_{ij});(i = 1, 2,..,NP;\ j = 1, 2,..,NG) \quad (14)$$

Where

W is an inertia weight value

R_1 and R_2 is the random number between 0 and 1

C_1 and C_2 are acceleration factors

p_{ij}^{best} is the best position for individual particle which yields lowest cost over all generations

G_j^{best} is the location of best particle in the entire population of all generations

The acceleration constants C_1 and C_2 in (14) represent the coefficient of the random acceleration terms that pull every particle toward pbest and gbest positions. Speed Vmax was, therefore, the sole parameter we regularly set it at regarding 10-20% of the dynamic vary of the variable on every dimension.

Step6: modification the position of the particle according to equation (15)

After the velocity is updated, the new location of j_{th} individual at the i_{th} dimension can be calculated as

$$p_{ij}^{new} = p_{ij} + v_{ij}^{new}\ (i = 1, 2,....NP;\ j = 1,2,.....,NG) \quad (15)$$

In the strategy of PSO, the particles best position p_{ij}^{best} and the global best position G_j^{best} are the key factors. The best position out of all p_{ij}^{best} is taken as G_j^{best}. Suitable selection of inertia weight in equation below provides balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. As originally developed, *w* often decrease linearly about 0.9 to 0.4 during a run

Step7: Loop to step two till a criterion is met, else

The individual that generates the latest gbest is the optimal generation power of each unit with the minimum total generation cost.

1.5 Simulations and Results

The procedure for solving ELD problems for the thermal power plant using Particle Swarm Optimization based has been implemented on Matlab R2013a software for windows. The effectiveness of the programme has been implemented on the Nigerian thermal power plant. The work was carried out on hp laptop computer with the following specifications: Processor: Intel® CPU T4300 @ 2.16GHz installed Memory (RAM): 4.00GB, system type: 32-bit operating system, hard disc: 350GB and windows operating system: windows 7.

The stimulation results were presented. Three different approaches were used by [1] to solve this problem; classical method (CM), hopfield neural network (HNN), micro genetic algorithm (μGA) and conventional genetic algorithm (CGA). They used three sets of power demand PD: 340MW, 850MW and 1150MW to test it on the IEEE 3 generating units, 6 bus test system before implementing on the Nigeria Hydrothermal Power plant. Particle swarm optimization was applied to the above test system for obtaining economic load dispatch of similar load requirements and was also implemented according to the flow chart shown above. For each sample load, under the same objective function and individual definition, good number of trials were performed to check the evolutionary process and to compare the quality of their solution and convergence characteristics

1.6 Simulation Results of the Nigerian Power System

The PSO based ELD is applied to the coordination of Nigerian thermal and hydro generating stations using data obtained from utility operator. The single line diagram of the system is shown in figure A1.

Table 1 presents the cost coefficients of the four Nigerian thermal power stations and their minimum and maximum loading limits obtained from [1]. The Nigerian power system grid is essentially a 31-bus, 330-kV network interconnecting four thermal generating stations and three hydro stations to the various load points. The hydrological data and the maximum and minimum load for the hydro units are obtained from [11] as shown in table 2. The computed quadratic cost functions for the hydro units are given in table 3.

Table.1. PHCN thermal generating units quadratic cost coefficients and power limits [1]

Generating Units Parameters					
Stations	Constant Cost Coefficient α	Linear Cost Coefficient β	Quadratic Cost Coefficient γ	P_{Gi}^{min} (MW)	P_{Gi}^{min} (MW)
Egbin	1278.00	13.10	0.031	275.00	1100.00
Afam	1998.00	56.0	0.092	135.00	540.00
Delta	525.74	-6.13	1.20	75.00	300.00
Sapele	6929.00	7.84	0.13	137.50	550.0

Table.2. Hydro Generating Units Parameters [11]

Power Stations Parameters	**KAINJI**	**JEBBA**	**SHIRORO**
Minimum Power (MW)	221	435	367
Maximum Power (MW)	350	490	450
Head Water Elevation (Meters)	133.91	102.74	364.36
Tail Water Elevation (Meters)	104.68	74.00	271.00
Gross Operating Head (Meters)	29.23	28.74	93.36
Average Turbine Discharge (M^3/Sec)	663	1260	377
Average Spillage (M^3/Sec)	0	0	0
Average Total Station Discharge (M^3/Sec)	663	1260	377
Computed Inflow (M^3/Sec)	1068	1191	481
Storage Differential	405	-69	104
Maximum Level for Spillage Commencement	141.73	103.3	359
Minimum Level below Which No Generation	137	99	355

Table.3. Hydro Unit cost functions [16]

Stations	Type	Characteristics of consumption
Kainji	Hydro	$W = 0.0013P_h^2 + 6P_h + 29.23$
Shiroro	Hydro	$W = 0.0012P_h^2 + 5\ P_h + 28.74$
Jebba	Hydro	$W = 0.0011P_h^2 + 3\ P_h + 93.36$

Convergence characteristic of the PSO based ELD for the Nigerian hydrothermal system is shown in figure 2.

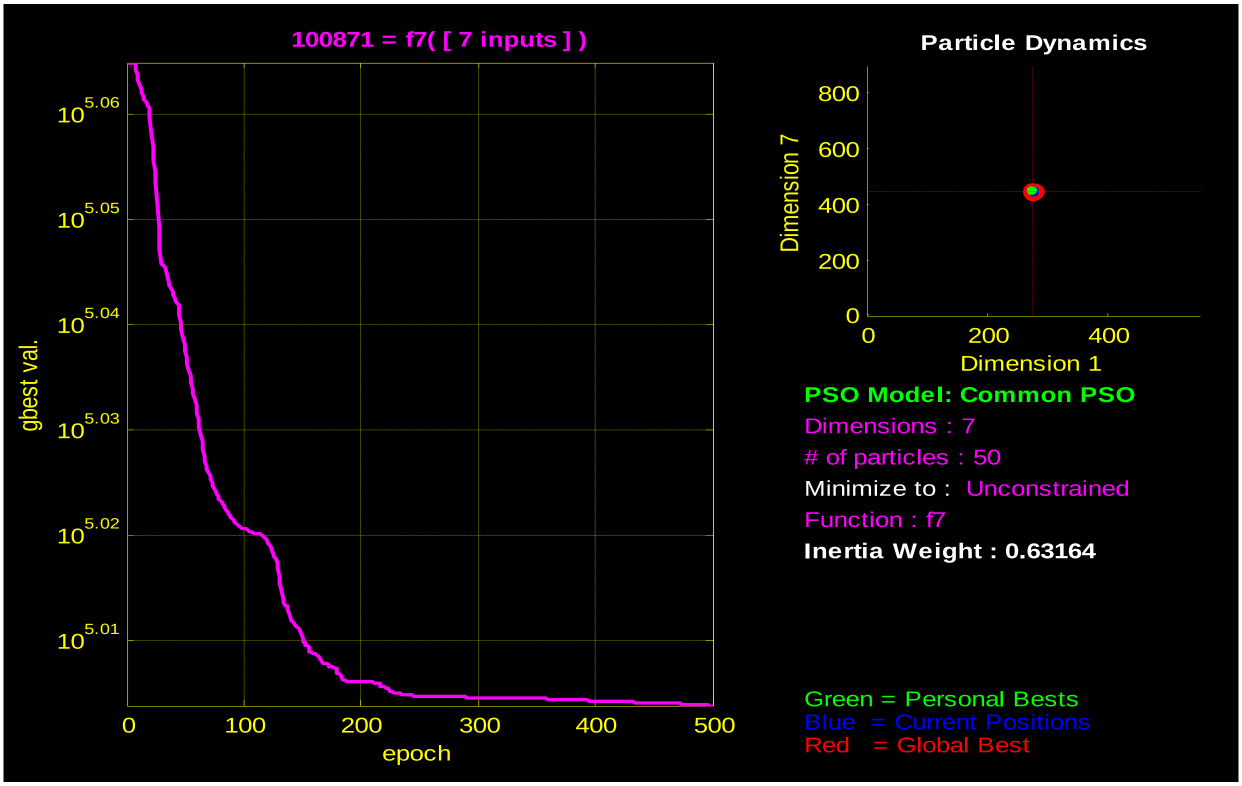

Figure.3. Convergence characteristics of PSO based ELD for Nigerian hydrothermal stations (P_D = 2890MW)

Table.4. Results of PHCN ELD considering losses compared with other techniques

Power Stations	Methods of solution: Genetic Algorithm [1]	Differential Evolution [7]	Particle Swarm Optimization
Egbin P_{G1} (MW)	814.56	818.08	1036.17
Afam P_{G2} (MW)	230.82	318.36	215.16
Delta P_{G3} (MW)	69.51	68.00	75.00
Sapele P_{G4} (MW)	457.79	265.93	274.99
Kainji (MW)	350	350	349.93
Shiroro (MW)	490	490	489.99
Jebba (MW)	450	450	449.87
Total power generated (MW)	2862.68	2860.37	2891.11
Total power demand P_D (MW)	2823.10	2823.10	2890.00
Total network losses P_L (MW)	130.28	129.26	1.1836
$P_D + P_L$ (MW)	2953.38	2952.36	2892.29
Total Cost $/hr	116946.55	107430.00	100871.00

II. CONCLUSION

The PSO based ELD result and the results of other methods are given in table 4. ELD problem was successfully solved using particle swarm optimization. The comparison of results for the 31-bus Nigerian grid system clearly shows that PSO is more accurate and hence a better approach to the optimization of ELD problem for the system. Almost all generation costs obtained by the PSO method were lower, thus verifying that the PSO method has better quality of solution and convergence characteristic. From the results obtained, the proposed PSO technique minimizes the total production cost and transmission losses better than GA and DE, except in some few cases where the DE also performed equally well and requires relatively less computational burden.

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IV. APPENDIX

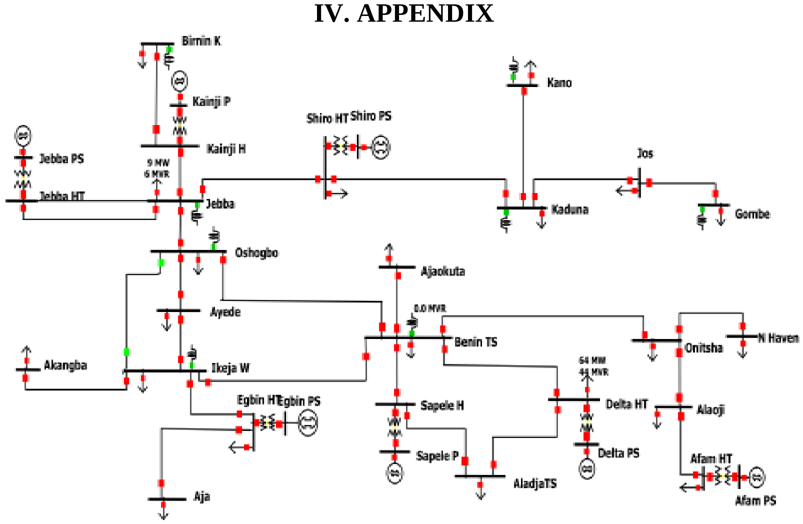

Figure A1: Single line diagram of Nigeria 330kV 31-bus grid systems

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