International Journal of Research in Engineering, Science and Management
Volume-3, Issue-2, February-2020
www.ijresm.com | ISSN (Online): 2581-5792

A Comparative Study of Particle Swarm Optimization and New PSO Time-Varying Acceleration Co-efficient for Solving Economic Load Dispatch Problem with Generator Constraints

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***Abstract*: This paper proposes a new particle swarm optimization approach with time varying acceleration coefficients (NPSOTVAC) for an extensive study of the economic load dispatch problem with valve point loading but normal PSO approach has been also performed. In this thesis transmission loss has not been included but valve point loading effect has been considered. This effect results in higher order nonlinearities in the input-output characteristics of a generator. For demonstrating the effectiveness of the proposed method three test systems viz. first one comprising of three generators, second one comprising of six generators & lastly ten generators system have been considered. The performance of the NPSOTVAC method has been compared with PSO strategy. The results show that the proposed NPSOTVAC strategy provides comparatively better solutions in terms of total fuel cost as compared to PSO method. Also, the global search capability is enhanced and premature convergence is avoided.**

***Keywords*: Economic load dispatch (ELD), Equality & in-equality constraints, NPSOTVAC, PSO, Valve point loading effect (VPL).**

1. Introduction

A. Economic Load Dispatch

1) Introduction of economic load dispatch

Electrical power system is designed and operated to meet the continuous variation of power demand. The remote location of power plant from the load centre has been identified as one of the reasons which caused high cost. The increase in fuel cost these days has also contributed to this phenomenon. Therefore, economic load dispatch is implemented in order to determine the output (generating) of each generator so that the total generation cost will be minimized. The generator's output has to be varied within limits so as to meet a particular load demand and losses within minimum fuel cost. Thus, Economic Load Dispatch (ELD) is one of the important topics to be considered in power system engineering. Economic Load Dispatch (ELD) is a method to schedule the power generation outputs with respect to the load demands, and to operate the power system most economically, or in other words, we can say that main objective of economic load dispatch is to allocate the optimal power generation from different unit at the lowest cost possible while meeting all system constraints.

Economic dispatch is the short-term determination of the optimal output of a number of electricity generation facilities, to meet the system load, at the lowest possible cost, subject to transmission and operational constraints. The Economic Dispatch Problem is solved by specialized computer software which should honour the operational and system constraints of the available resources and corresponding transmission capabilities. In the US Energy Policy Act of 2005 the term is defined as "the operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognising any operational limits of generation and transmission facilities".

The main idea is that in order to serve load at minimum total cost, the set of generators with the lowest marginal costs must be used first, with the marginal cost of the final generator needed to meet load setting the system marginal cost. This is the cost of delivering one additional MW of energy onto the system. The historic methodology for economic dispatch was developed to manage fossil fuel burning power plants, relying on calculations involving the input/output characteristics of power stations.

This paper is concerned with the economic dispatch problem of all thermal systems only. It is to be note that all the generating units in a system do not participated in the economic dispatch. Nuclear units and very large steam units are run at constant MW setting as it is desirable (due to some technical reasons) to maintain the output of such units at as constant a level as possible. Rest of the units those participate in economic load dispatch will be called controllable units. Fuel costs in base-load units then appear as a fixed cost and do not appear in the economic dispatch problem. We consider the minimization of those costs that, by proper strategy, we can control, i.e. the fuel costs in the controllable units.

In real world power systems, electrical power generation units are not located at the same distance from the center of the load. Apart from that, electrical power generation costs for each of these units are also different in terms of fuel, maintenance, labor etc. Due to this variety of power generation costs, the most important problem is to prepare a schedule which is the most efficient and economical that can be followed by a power system. In recent years, many optimization methods on the problem of economic load dispatch, as a constraint optimization problem, have been studied where all researches try to find which method is more efficient and faster in execution and also easier to implement.

2) Different Constraint in ELD

There are two types of constraints mainly. Inequality and equality constraints. Voltage constraints V_{min} V_{max}; min max. Generator constraints KVA loading of generator should not exceed prescribed value $P_{min} \leq P \leq P_{max}$; $Q_{min} \leq Q \leq Q_{max}$. Equality constraints are real and reactive power balance.

3) Cost Function of ELD

The economic load dispatch(ELD) problem is one of the important optimization problems in a power system. Traditionally, in the ELD problem, the cost function for each generator has been approximately represented by a single quadratic function. It is more realistic, however, to represent the generation cost function for fossil fired plants as a segmented piecewise quadratic function, as in the case of valve point loading. Some generation units, especially those units which are supplied with multiple fuel sources (gas and oil), are faced with the problem of determining which is the most economical fuel to be burnt. As fossil fuel costs increase, it becomes even more important to have a good model for the production cost of each generator. Therefore, a more accurate formulation is obtained for the ELD problem by expressing the generation cost function as a piecewise quadratic function. This approach can be applied to generators supplied with various fuels as well as valve point loading problems.

B. Introduction of Particle Swarm Optimization (PSO) & New PSO with Time-Varying Acceleration Coefficients (NPSOTVAC) Method

1) Introduction of Soft Computing Technique

Over the years, many efforts have been made to solve the ELD problem, incorporating different kinds of constraints or multiple objective troughs various mathematical programming and optimization techniques. The convention methods include Newton Raphson method, Lambda Iteration method, Base point and Participation Factor method, Gradient method, etc. However, these classical dispatch algorithms require the incremental cost curves to be monotonically increasing or piece-wise linear. The input/output characteristics modern units are inherently nonlinear (with valve-point effect, rate limits etc) and having multiple local minimum points in the cost function. Their characteristics are approximated to meet the requirements of classical dispatch algorithms leading to sub optimal solutions and therefore, resulting in huge revenue loss over the time. In this respect stochastic search algorithms like genetic algorithm (GA), evolutionary strategy (ES), evolutionary programming (EP), particle swarm optimization (PSO) and simulated annealing (SA) may prove to very efficient in solving highly nonlinear ELD problem without any restrictions on the shape of the cost curves.

2) The Basics of Particle Swarm Optimization

Particle swarm optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. PSO optimizes a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position but, is also guided toward the best known positions in the search-space, which are updated as better positions are found by other particles. This is expected to move the swarm toward the best solutions. PSO is originally attributed to Kennedy, Eberhart and was first intended for simulating social behaviour, as a stylized representation of the movement of organisms in a bird flock or fish school. The algorithm was simplified and it was observed to be performing optimization.

3) Steps of Particle Swarm Optimization

There are three steps of particle swarm optimization.

Initialization

All parameters are randomly initialized within their operating limits.

Update

All parameters are updating using the updating equation.

Selection

This step is based on 'Survival of the fittest'. The updated vector is compared with the initialized vector and the one with a better fitness is admitted to next generation.

4) The Basics of New PSO with Time-Varying Acceleration Coefficients (NPSOTVAC) Method

In PSO, tuning of parameters with time plays an important role in finding the optimum solution accurately and efficiently. A new PSO technique where acceleration coefficients are varied with time are used in this paper to solve the complex problem of ELD with valve point loading effect including & excluding.

Kennedy and Eberhart stated that a relatively higher value of the cognitive component, compared with the social component, results in roaming of individuals through a wide search space. On the other hand, a relatively high value of the social component leads particles to a local optimum prematurely.

2. Literature survey

A method is devolved [1] for solving the Economic Load Dispatch (ELD) by changing it from constrained nonlinear programming problem to a sequence of constrained linear programming problems. Proposed Hessian based optimization

[2] method has much higher convergence efficiency that those techniques based on the gradient of the objective function. In the literature this handling equality constraints through penalty functions added to the cost. A several approaches have been discussed to overcome the drawbacks of classical economic load dispatch ELD problem. Some of these methods have been based on successive linear programming and successive quadratic programming described by different authors in literature. Different methods for power system operation has been discussed by Miller and Malinnowski [3]. The economic load dispatch problem [4] is a quadratic programming problem and solved using Wolfe's algorithm. The quadratic programming algorithm does not require the use of penalty factors or the determination of gradient step size which can cause convergence difficulties. The parametric quadratic programming method [5] is a solving an economic load dispatch problem with dc load flow type network security constraints.

The method is handling real power transmission constraints on branch flows and inter-area exchanges to supplement the classic ED formulation using dual quadratic programming [6]. The proposed an Improved Differential Evolution (IDE) algorithm to solve Economic Load Dispatch (ELD) problem with non-smooth fuel cost curves considering transmission losses, power balance and capacity constraints. The proposed IDE varies from the Standard Differential Evolution (SDE) algorithm in terms of three basic factors. Operation has been discussed by Surekha P, and S. Sumathi [8]. Simulated Annealing (SA) algorithm is applied to solve economic load dispatch (ELD) problems. The proposed method for solving ELD problems is verified by using 3, 13, 40 and 18 generator test systems, out of which the first three test cases are with valve-point loading effects [9]. A method of traditional approach to solve the ELD problem using Lambda iteration method (LIM) in MATLAB environment for two generator units and four separate cases has to be considered with and without transmission losses and generator constraints [10].

Presentation of robust [11] and efficient method for solving transient stability constrained optimal power flow problems based on DE, which is a new branch of evolutionary algorithms with strong ability in searching global optimal solutions of highly nonlinear and non-convex problems. The Economic Load Dispatch (ELD) problem[12] with security constraints in thermal units, which are capable of obtaining economic scheduling for utility system, the PSO method, a new velocity strategy equation is formulated suitable for a large scale system and the features of constriction factor approach are also incorporated.DE algorithm [13] for solving ELD problems in power systems, DE has proven to be effective in solving many real worlds constrained optimization problems in different domains. The coordination to the economic load dispatch [14] and regulation functions of automatic generation control in power systems. The point of view taken is that such coordination appropriately taken place at the regulation or load frequency control level. The genetic-based algorithm [15] to solve an economic dispatch problem for valve point discontinuities, thus the constrains of classic Lagrange technique on unit curve are circumvented.

Kumari and Sydulu [16] presented Genetic Algorithm (FGA) for solving Economic Load Dispatch (ELD) problem, GA's perform powerful global searches, but their long computation times limit them when solving large scale optimization problems. Analysis of efficient and reliable modern programming approach is using quadratic programming (QP) and general algebraic modeling system (GAMS) to solve economic load dispatch (ELD) problem. It easily takes care of different equality and inequality constraints of the power dispatch problem to find optimal solution [17]. Particle swarm optimizer [18] combined with roulette selection operator to solve the economic load dispatch problem of thermal generators of a power system. Several factors such as quadratic cost functions with valve point loading, transmission Loss, generator ramp rate limits and prohibited operating zone are considered in the computation models. A novel binary successive approximation-based evolutionary search strategy has been proposed to solve the economic-emission load dispatch problem by searching the generation pattern of committed units [19]. The proposed method minimizes the fuel cost of generators using a hybrid quantum-inspired PSO. Inclusion of such constraints presents ELD as a non-smooth and non-convex optimization problem. The problem formulations with objective function and considered constraints will describes the hybrid quantum-based particle swarm optimization (HQPSO) with a little discussion about traditional PSO and its transformation towards HQPSO [20].

A novel modified Bacterial Foraging Technique (BFT) [21] is used to solve economic load dispatch problems. A new optimization technique efficient hybrid simulated annealing algorithm (EHSA) for both convex & non-convex ELD problem. The mutation operator of differential evolution is used in particle swarm optimization to improve its performance & it is hybridized with simulated annealing to get EHSA technique [22]. An efficient and reliable Biogeography–based optimization (BBO) algorithm [23] is used to solve both convex and non-convex Economic load dispatch problem (ELD) with Ramp rate limit of thermal power plants. Normally proposed power generation, spinning reserve and emission costs are simultaneously considered in the objective function of the proposed ELD problem. In this condition, if the valve-point effects of thermal units are considered in the proposed emission, reserve and economic load dispatch (ERELD) problem, a non-smooth and non-convex cost function will be obtained. A hybrid method that combines the bacterial foraging (BF) algorithm with the Nelder–Mead (NM) method (called BF–NM algorithm) is used to solve the problem [24]. An economic emission load dispatch (EELD) problem is solved to minimize the emission of nitrogen oxides (NOX) and fuel cost, considering both thermal generators and wind turbines. To find the optimum emission dispatch, optimum fuel cost, best compromising emission and fuel cost, a newly developed optimization technique, called Gravitational Search Algorithm (GSA) has been applied. IEEE 30-bus system having six conventional thermal generators has been considered as test system [25].

Ant Colony Optimization (ACO) technique [26] is proposed to be combined with Differential Evolution (DE) and cloning process, and Differential Evolution Immunized Ant Colony Optimization (DEIANT) technique in solving economic load dispatch problem. The combination creates a new algorithm that will be termed as Differential Evolution Immunized Ant Colony Optimization (DEIANT). DEIANT was utilized to optimize economic load dispatch problem. In order to overcome the drawbacks of conventional methods, Artificial Intelligent (AI) techniques likes like Genetic Algorithm (GA), Neural Networks (NN), Artificial Immune systems (AIS) and Fuzzy Logics etc. are used. One such AI technique used is Artificial Bee Colony optimization (ABC) inspired from the foraging behaviour of bees. The ABC [27] is applied for ELD and compared with the other AI techniques. Weight-Improved Particle Swarm Optimization (WIPSO) [28] method is proposed for computing Optimal Power Flow (OPF) and ELD problems, to evaluate the accuracy, convergence speed and applicability of the proposed method. The OPF results of IEEE 30 bus system by WIPSO are compared with traditional particle swarm optimization, genetic algorithm, and Differential Evolution (DE) and Ant Colony Optimization (ACO) methods.

The performance [29] of the proposed algorithm is compared with standard Improved Fast Evolutionary Programming (IFEP) techniques, to used genetic algorithm (GA) tuned differential evolution (DE) method for solving economic dispatch (ED) problem with non-smooth cost curves. This Evolutionary optimization techniques [31] namely Genetic Algorithm (GA) and Differential Evolution (DE) is proposed to solve ELD in the electric power system. According to Palanichamy and Shrikrishna [30] discussed Simple algorithm for economic power dispatch for optimizing the problem while satisfying a set of system operating constraints, including constraints dictated by Wood and Woolenberg [31]. Heuristic optimization method and Quantum-inspired Particle Swam Optimization (QPSO) [32] is used to solve valve-point Economic load dispatch problem. It has stronger search ability and quicker convergence speed, not only because of the introduction of quantum computing theory, but also due to two special implementations: self-adaptive probability selection and chaotic sequences mutation. Alsumit et al. proposed a hybrid GA-PS-SQP method [33]to solve power system valve-point economic dispatch problems. The applied multi-objective differential evolution (MODE) algorithm [34] is proposed to solve environmental/economic power dispatch (EED) problem.

3. Overview of Economic Load Dispatch

A. *The economic operation of power system*

Since an engineer is always concerned with the cost of products and services, the efficient optimum economic operation and planning of electric power generation system have always occupied an important position in the electric power industry. With large interconnection of the electric networks, the energy crisis in the world and continuous rise in prices, it is very essential to reduce the running charges of the electric energy. A saving in the operation of the system of a small percent represents a significant reduction in operating cost as well as in the quantities of fuel consumed. The classic problem is the economic load dispatch of generating systems to achieve minimum operating cost.

This problem area has taken a subtle twist as the public has become increasingly concerned with environmental matters, so that economic dispatch now includes the dispatch of systems to minimize pollutants and conserve various forms of fuel, as well as achieve minimum cost. In addition, there is a need to expand the limited economic optimization problem to incorporate constraints on system operation to ensure the security of the system, thereby preventing the collapse of the system due to unforeseen conditions. However closely associated with this economic dispatch problem is the problem of the proper commitment of any array of units out of a total array of units to serve the expected load demands in an 'optimal' manner. For the purpose of optimum economic operation of this large scale system, modern system theory and optimization techniques are being applied with the expectation of considerable cost savings. The operation economics can again be subdivided into two parts

1. Problem of economic dispatch, which deals with determining the power output of each plant to meet the specified load, such that the overall fuel cost is minimized.
2. Problem of optimal power flow, which deals with minimum – loss delivery, where in the power flow, is optimized to minimize losses in the system.

During operation of the plant, a generator may be in one of the following states:

1. Base supply without regulation: the output is a constant.
2. Base supply with regulation: output power is regulated based on system load.
3. Automatic non-economic regulation: output level changes around a base setting as area control error changes.
4. Automatic economic regulation: output level is adjusted, with the area load and area control error, while tracking an economic setting.

Regardless of the units operating state, it has a contribution to the economic operation, even though its output is changed for different reasons. The factors influencing the cost of generation are the generator efficiency, fuel cost and transmission losses. The most efficient generator may not give minimum cost, since it may be located in a place where fuel cost is high. Further, if the plant is located far from the load centers, transmission losses may be high and running the plant may become uneconomical. The economic dispatch problem basically determines the generation of different plants to minimize total operating cost. Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital investment of millions of rupees. The economic dispatch is however determined in terms of fuel cost per unit power generated and does not include capital investment, maintenance, depreciation, start-up and shut down costs etc.

B. Economic Load Dispatch

The Economic Load Dispatch (ELD) can be defined as the process of allocating generation levels to the generating units, so that the system load is supplied entirely and most economically. For an interconnected system, it is necessary to minimize the expenses. The Economic Load Dispatch is used to define the production level of each plant, so that the total cost of generation and transmission is minimum for a prescribed schedule of load. The objective of economic load dispatch is to minimize the overall cost of generation. The method of economic load dispatch for generating at different loads must have total fuel cost at minimum point.

In a typical power system, multiple are implemented to provide enough total output to satisfy a given total consumer demand. Each of these generating stations can and usually does, have a unique cost-per hour characteristic for its output operating range. A station has incremental operating costs for fuel and maintenance, and fixed costs associated with the station itself that can be quite considerable in the case of a nuclear power plant, for example things get even more complicated when utility try to account for transmission line losses, in the seasonal change associated with hydroelectric plants.

C. Load Scheduling

The operation of a modern power system has become very complex. It is necessary to maintain frequency and voltage within limit in addition to ensuring reliability of power supply and for maintaining the frequency and within limit it is essential to match the generation of active and reactive power with the load demand. For ensuring reliability of power system it is necessary to put additional generation capacity into the system in the event of outage of generating equipment at some station. The total interconnected network is controlled by the load dispatch centre. The load dispatch centre allocates the MW generation to each grid depending upon the prevailing MW demand in the area. Each load dispatch centre controls load and frequency of its own by matching generation in various generating stations with total required MW demand plus MW losses. Therefore, the task of load control centre is to keep the exchange of power between various zones and system frequency at desired values. It is not always necessary that all the units of a plant are available to share a load. Some of the units may be taken off due to scheduled maintenance. Also it is not necessary that the less efficient units are switched off during off peak hours. There is a certain amount of shut down and startup costs associated with shutting down a unit during the off peak hours and servicing it back on-line during the peak hours. To complicate the problem further, it may take about eight hours or more to restore the boiler of a unit and synchronizing the unit with the bus. To meet the sudden change in the power demand, it may therefore be necessary to keep more units than it necessary to meet the load demand during that time. This safety margin in generation is called spinning reserve. The optimal load dispatch problem must then incorporate this start up and shut down cost for without endangering the system security. The power generation limit of each unit is then given by the inequality constraints i.e. $P_{min,}$ P, P_{max}. The maximum limit P_{max} is the upper limit of power generation capacity of each unit. On the other hand, the lower limit P_{min} pertains to the thermal consideration of operating a boiler in a thermal or nuclear generating station. An operational unit must produce a minimum amount of power such that the boiler thermal components are stabilized at the minimum design operating temperature.

D. Necessity of Generation Scheduling

In a practical power system, the power plants are not located at the same distance from the centre of loads and their fuel costs are different. Also under normal operating, the generation capacity is more than the total load demand and losses. Thus, there are many options for scheduling generation. In an interconnected power system, the objective is to find the real and reactive power scheduling of each power plant in such a way so as to minimise the operating cost. This means that the generators real and reactive powers are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost. This is called the “Economic load dispatch” (ELD) problem. The objective functions, also known as cost functions may present economic cost system security or other objectives. The transmission loss formula can be derived and the economic load dispatch of generation based on the loss formula can also be obtained. The Loss coefficients are known as B-coefficients. A major challenge for all power utilities is not only to satisfy the consumer demand for power, but to do so at minimal cost. Any given power system can be comprised of multiple generating stations having number of generators and the cost of operating these generators does not usually correlate proportionally with their outputs; therefore, the challenge for power utilities is to try to balance the total load among generators that are running as efficiency as possible. The economic load dispatch (ELD) problem assumes that the amount of power to be supplied by a given set of units is constants for a given interval of time and attempts to minimize cost of supplying this energy subject to total cost incurred in the system and constraints over the entire dispatch period. Therefore, the main aim in the economic load dispatch problem is to minimize the total cost of generating real power (production cost) at various stations while satisfying the loads and the losses in the transmission links.

E. Fuel cost

The primary objective of the ELD problem is to minimize the cost function and determine the most economical loadings of the generators such that the load demand in a power system can be met. It can be described as an optimization process with the following objective function and equality &in-equality constraints.

$$\begin{cases} Min.F = \sum_{i=1}^{N} F_i(P_i) \\ \sum_{i=1}^{N} P_i - (P_D + P_L) = 0 \end{cases} \quad (1)$$

Where,

$F_i(P_i)$	Fuel cost function
P_i	Generated power of unit
N	Number of online units
P_D	System load demand
P_L	Transmission loss

When transmission losses are neglected, $P_L = 0$.

The fuel cost function of ith unit can be defined by

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \quad (2)$$

Where a_i, b_i, c_i are the cost coefficients of unit i.

F. Fuel Cost Including Valve Point Loading Effect

Economic load dispatch is one of the most important problems to be solved on the operation and planning of a power system the primary concern of an ELD problem is the minimization of its objective function. The total cost generated that meets demand & satisfies all other constraints associated is selected as the objective function. The ELD problem objective function is formulated mathematically in (1) & (2) if given conditions are satisfied. Due to presence of valve point loading effect non-linearity & discontinuity of the ELD is increased, that why equation 2 can be modified as (3) and (4).

$$F_i'(P_i) = F_i(P_i) + abs\left(e_i \sin\left(f_i\left(P_i^{\min} - P_i\right)\right)\right) \quad (3)$$

$$F_i'(P_i) = a_i P_i^2 + b_i P_i + c_i + abs\left(e_i \sin\left(f_i\left(P_i^{\min} - P_i\right)\right)\right) \quad (4)$$

e_i and f_i are the valve point loading effect coefficients of the ith generator.

G. Constraints

Generally, there are two types of constraints viz. (i) Equality constraints (ii)in-equality constraints

(i) Equality constraints:

System Power Balance:

The total power output of generator should be able to satisfy the load demand & transmission loss. At a particular time, interval t, mathematically this constraint can be defined as

$$\sum_{i=1}^{N} P_i(t) = P_D(t) + P_L(t) \quad (5)$$

Where $P_D(t)$ is the load demand at time t and $P_L(t)$ is the system's transmission loss. The system transmission network loss is computed by the Kron's loss formula, which represents loss as a function of the output level of the system-generating units.

$$P_L(t) = P^T[B]P + B_0 P + B_{00} \quad (6)$$

Here B is the matrix of loss coefficients. The above equation can be broken down as follows

$$P_L(t) = \sum_{j=1}^{N}\sum_{k=1}^{N} P_j(t) B_{jk} P_k + \sum_{j=1}^{N} P_j B_{j0} + B_{00} \quad (7)$$

(ii) In-equality constraints:

(a) Operating power limit:

The generator's output should operate within their ranges.

$$P_i^{\min} \le P_i \le P_i^{\max} \quad (8)$$

Where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum operating limits of generator i.

(b) Ramp Rate Limit:

Normally in ELD, generators' outputs were assumed to be handled instantaneously. Generally, the output is bounded by the ramp up or ramp down limits which depends on the nature of generators' power increasing or decreasing stage. According to the increasing and decreasing operation of the generators, ramp rate limit constraints are described below.

As generation increases

$$P_i(t) - P_i(t-1) \le UR_i \quad (9)$$

As generation decreases

$$P_i(t-1) - P_i \le DR_i \quad (10)$$

Where UR_i and DR_i are the up and down rate limit for generation i respectively. If we combine this equation with operating power limit equation, then

$$\max(P_i^{min}, P_i(t-1) - DR_i) \le P_i(t) \le \min(P_i^{max}, P_i(t-1) + URi) \quad (11)$$

(c) Generator's Prohibited Zone:

The Prohibited Operating Zones in the input–output performance curve for a typical thermal unit contains some prohibited operating zones due to the steam valve operation or vibration in a shaft bearing. Mathematically those zones for i_{th} unit are defined as,

$$P_i^{\min} \le P_i(t) \le P_{i,1}^{l}$$
$$P_{i,k-1}^{u} \le P_i(t) \le P_{i,k}^{l}; \quad k = 2,3,\ldots\ldots\ldots nz_i \qquad (12)$$
$$P_{i,nz_i}^{\ u} \le P_i(t) \le P_i^{\max}$$

Where $P_{i,k}^{l}$ and $P_{i,k}^{u}$ are the lower and upper bound of the kth prohibited zone of generator i.

nz_i represents the number of prohibited zones for ith generation.

4. Introduction of Particle Swarm Optimization & New PSO with Time-varying Acceleration Coefficient (NPSOTVAC) Method

A. *Classical PSO*

PSO, developed by Eberhart and Kennedy in 1995, is one of the evolutionary computation techniques. PSO, like GA, is a population based optimization algorithm. Instead of the survival of the fittest, it is the simulation of social behavior that motivates PSO. Here, the population is called 'swarm'. Each potential solution, called particle, is given a random velocity and is flown through the solution space (similar to the search process for food of a bird swarm) looking for the optimal position. The particles have memory and each particle keeps track of its previous best position, called *pbest* and corresponding fitness. The swarm remembers another value called *gbest*, which is the best position discovered by the swarm. If a particle discovers a promising new solution, all the other particles will move closer to it. Based on PSO concept, mathematical equations for the searching process are:

Velocity updating equation:

$$v_{id}^{k+1} = w * v_{id}^{k} + c1 * r1 * \left(pbest_{id} - x_{id}^{k}\right) + c2 * r2 * \left(gbest_{id} - x_{id}^{k}\right) \qquad (13)$$

Position updating equation:

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \qquad (14)$$

Where x_{id}^{k}, x_{id}^{k+1} are the position of d^{th} dimension (variable) of the i^{th} particle at k^{th} and $(k+1)^{th}$ iteration; v_{id}^{k}, v_{id}^{k+1} are the velocity of the d^{th} dimension of the i^{th} particle at the k^{th} and the $(k+1)^{th}$ iteration; $c1, c2$ are the cognitive and the social parameters; $r1 \& r2$ are random numbers uniformly distributed within [0, 1]; $pbest_{id}$ is the best position of the d^{th} dimension of the i^{th} particle; $gbest_d$ is the group best position of the d^{th} dimension and w is the inertia weight factor.

B. *New-PSO with Time-varying Acceleration Coefficient (NPSOTVAC)*

In PSO, tuning of parameters with time plays an important role in finding the optimum solution accurately and efficiently. A new PSO technique where acceleration coefficients are varied with time are used in this paper to solve the complex problem of ELD with valve point loading effect including & excluding. Kennedy and Eberhart stated that a relatively higher value of the cognitive component, compared with the social component, results in roaming of individuals through a wide search space. On the other hand, a relatively high value of the social component leads particles to a local optimum prematurely. In population-based optimization methods, the policy should be to encourage the individuals to roam through the entire search space, during the initial part of the search, without clustering around local optima. During the latter stages, however convergence towards the global optima should be encouraged, to find the optimum solution efficiently. The idea behind TVAC is to enhance the global search in the early part of the optimization and to encourage the particles to converge towards the global optima at the end of the search. This is achieved by changing the acceleration coefficients C_1 & C_2 with time in such a manner that the cognitive component is reduced while the social component is increased as the search proceeds.

C1=(C1F-C1I)*(Iter/Iter_max)+C1I
C2=(C2F-C2I)*(Iter/Iter_max)+C2I (15)

Where C_1, C_{1F}, C_{1I} cognitive, final & initial value of cognitive acceleration constants (user defined). Where C_2, C_{2F}, C_{2I} social, final & initial value of social acceleration constants (user defined). In the NPSOTVAC the cognitive & social acceleration coefficients vary in the following way i.e. $2.5 \ge C_1 \ge 0.5$ & $0.5 \le C_2 \le 2.5$ respectively.

5. Result and Discussion

The applicability of the PSO & NPSOTVAC algorithm for practical application has been tested in three cases. Case 1 is three units system without considering loss [35], case 2 is six units system [36], case 3 is ten generating units [37]. To verify the efficiency in three cases including power balance, power generation limits constraints alone are included for the sake of comparison with other techniques reported in the literature. The programs are developed using MATLAB 7.01 and the system configuration is Pentium IV processor with 3.2 GHz speed and 2 GB RAM. Computational results are based on 50 trials.

Setting of PSO and NPSOTVAC parameter

As in other optimization techniques, parameters such as population size are to be determined before its implementation. It is to be determined that an intermediate value for the population size gives an increase in efficiency and a higher converged score for the same number of generations. Following parameters are most fit for the PSO & NPSOTVAC algorithm.

Population size: 100
Maximum iteration: 100

A. *Case study-1:*

1) *ELD for three generator system*

Optimum Solution Using PSO & NPSOTVAC Algorithm:

The description of the results by utilizing PSO & NPSOTVAC without considering losses is detailed. A system of three Generator units with the effects of PSO & NPSOTVAC Algorithm is studied in this test. Table 2 and 4 gives power output for three generator units system without considering transmission loss & valve point loading effect for 585 MW and 700 MW respectively. Table 3 and 5 gives power output for three generating units system without transmission loss but including valve point loading effect for 585 MW and 700 MW respectively. Table 6 and 7 provides the comparison study of two methods. Fig. 2 and 3 gives graph between No. of Iterations and Cost in R/hr for load of 585 MW without considering loss and valve point loading effect of 3 generators system using NPSOTVAC and PSO method respectively. Fig. 4 and 5 gives graph between No. of Iterations and Cost in $/hr for load of 700 MW without considering loss and valve point loading effect of 3 generators system using NPSOTVAC and PSO method respectively. Fig. 6, 7, 8 and 9 gives same graph but with considering valve point loading effect.

Table 1
Specification for three generators without loss test system [35]

Gen	ai	bi	ci	di	ei	Pmax	Pmin
P1	0.00156	7.92	561	300	0.031	600	100
P2	0.00194	7.85	310	200	0.042	400	100
P3	0.00482	7.97	78	150	0.063	150	50

Table 2
Power o/p for the three generator units system without considering transmission losses & valve point loading (Power Demand=585MW)

Power output(MW)	NPSOTVAC	PSO
P1	309.0363	221.7144
P2	188.1733	251.8942
P3	87.7904	111.3914
Total cost($/hr)	**5821.40**	**5822.31**

Table 3
Power o/p for the three generator units system without considering transmission losses & but including valve point loading (Power Demand=585MW)

Power output(MW)	NPSOTVAC	PSO
P1	297.1238	305.8828
P2	174.5093	210.4348
P3	113.3669	68.6824
Total cost($/hr)	6001.033	6193.1851

Table 4
Power o/p for the three generator units system without considering transmission losses & valve point loading (Power Demand=700MW)

Power output(MW)	NPSOTVAC	PSO
P1	256.6980	322.5797
P2	335.9274	303.4520
P3	107.3746	73.9683
Total cost($/hr)	6838.47	6838.70

Table 5
Power o/p for the three generator units system without considering transmission losses & but including valve point loading (Power Demand=700MW)

Power output(MW)	NPSOTVAC	PSO
P1	427.5067	427.9808
P2	172.8805	165.3602
P3	99.6128	106.6590
Total cost($/hr)	7094.94	7222.7261

Table 6
Comparison between NPSOTVAC & PSO for three generating units system without transmission loss & valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
585	5821.40	5822.31
700	6838.47	6838.70

Table 7
Comparison between NPSOTVAC & PSO for three generating units system without transmission loss but including valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
585	6001.033	6193.1851
700	7094.94	7222.7261

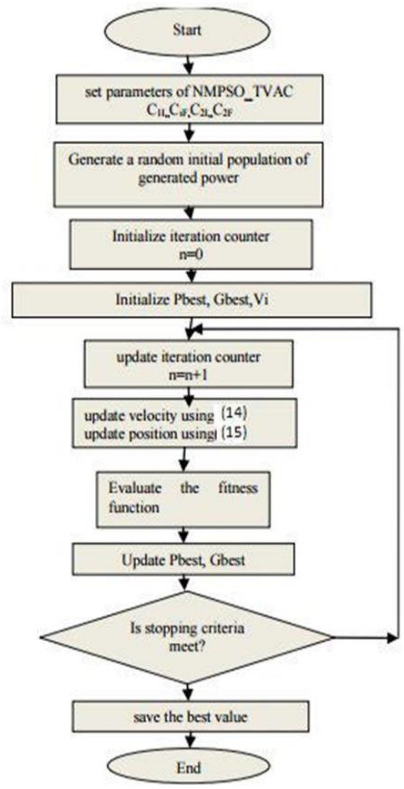

Fig. 1. Flow Chart of NPSOTVAC

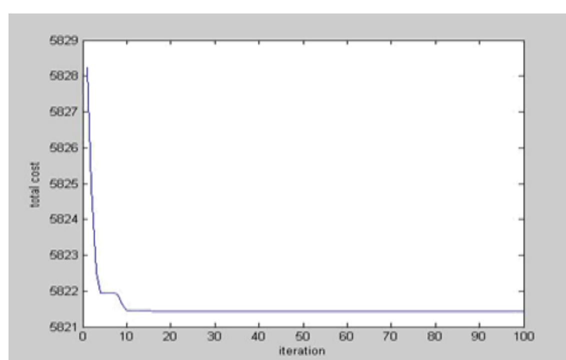

Fig. 2. Graph between No. of iterations & cost in $/hr for load of 585 MW without considering loss & valve point loading effect for 3 generators system using NPSOTVAC converged at 5821.40 $/hr

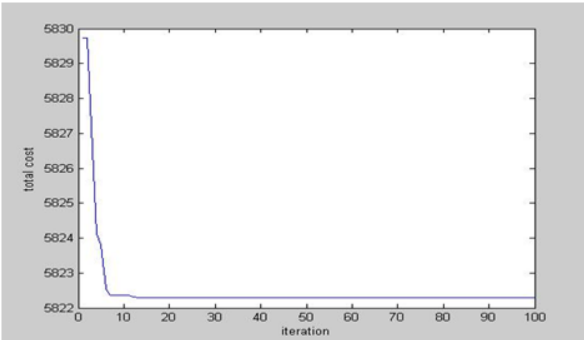

Fig. 3. Graph between No. of iterations & cost in $/hr for load of 585 MW without considering loss & valve point loading effect for 3 generators system using PSO converged at 5822.31 $/hr

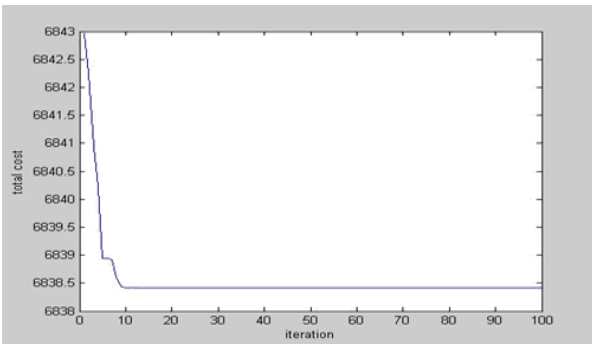

Fig. 4. Graph between No. of iterations & cost in $/hr for load of 700 MW without considering loss & valve point loading effect for 3 generators system using NPSOTVAC converged at 6838.47 $/hr

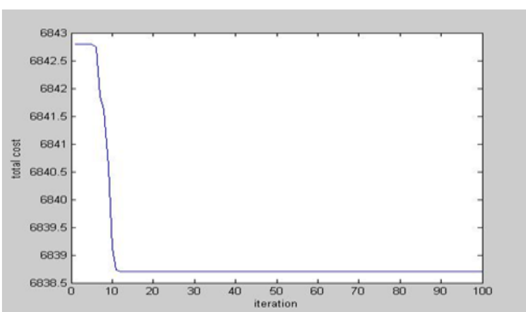

Fig. 5. Graph between No. of iterations & cost in $/hr for load of 700 MW without considering loss & valve point loading effect for 3 generators system using PSO converged at 6838.70 $/hr

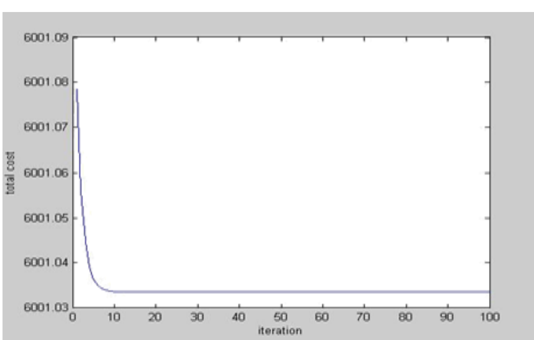

Fig. 6. Graph between No. of iterations & cost in $/hr for load of 585 MW without loss but including valve point loading effect for 3 generators system using NPSOTVAC converged at 6001.033 $/hr

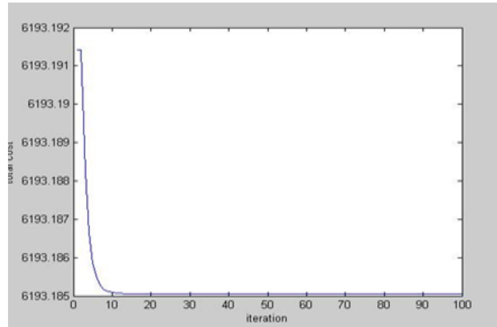

Fig. 7. Graph between No. of iterations & cost in $/hr for load of 585 MW without loss but including valve point loading effect for 3 generators system using PSO converged at 6193.1851 $/hr

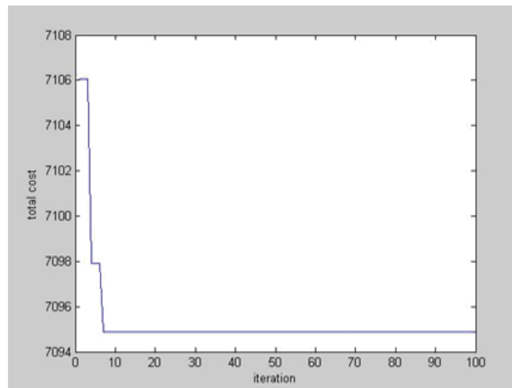

Fig. 8. Graph between No. of iterations & cost in $/hr for load of 700 MW without loss but including valve point loading effect for 3 generators system using NPSOTVAC converged at 7094.94 $/hr

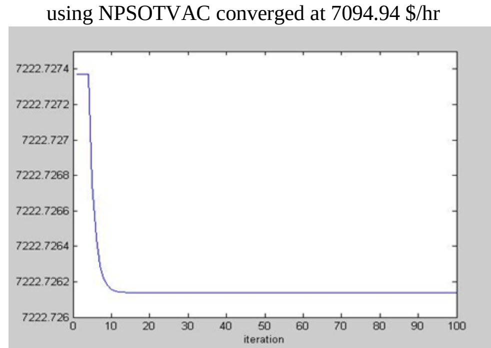

Fig. 9. Graph between No. of iterations & cost in $/hr for load of 700 MW without loss but including valve point loading effect for 3 generators system using PSO converged at 7222.7261 $/hr

B. Case study-2

1) ELD for six generator system

Optimum Solution Using PSO & NPSOTVAC Algorithm

The description of the results by utilizing PSO & NPSOTVAC without considering losses is detailed. A system of three Generator units with the effects of PSO & NPSOTVAC Algorithm is studied in this test. Table 5.9 and 5.11 gives power output for six generator units system without considering transmission loss & valve point loading effect for 800 MW and 1200 MW respectively. Table 5.10 and 5.12 gives power output for six generating units system without transmission loss but including valve point loading effect for 800 MW and 1200 MW respectively. Table 5.13 and 5.14 provides the comparison study of two methods. Fig 10 and 11 gives graph between No. of Iterations and Cost in R/hr for load of 800 MW without considering loss and valve point loading effect of 6 generators system using NPSOTVAC and PSO method respectively. Fig 12 and 13 gives graph between No. of Iterations and Cost in R/hr for load of 1200 MW without considering loss and valve point loading effect of 6 generators system using NPSOTVAC and PSO method respectively. Fig 14,15,16 and 17 gives same graph but with considering valve point loading effect.

Table 8
Specification for six generators without loss test system [36]

Gen	ai	bi	ci	di	ei	Pmax	Pmin
P1	0.007	7	240	300	0.031	500	100
P2	0.0095	10	200	150	0.063	200	50
P3	0.009	8.5	220	200	0.042	300	80
P4	0.009	11	200	100	0.08	150	50
P5	0.008	10.5	220	150	0.063	200	50
P6	0.0075	12	190	100	0.084	120	50

Table 9
Power o/p for the six generator units system without considering transmission losses & valve point loading (Power Demand=800MW)

Power output (MW)	NPSOTVAC	PSO
P1	180.5858	204.8939
P2	74.5179	117.1741
P3	274.6353	196.6263
P4	58.7676	133.0741
P5	137.9566	80.3221
P6	73.5368	67.9094
Total cost($/hr)	9499.20	9533.51

Table 10
Power o/p for the six generator units system without considering transmission losses & but including valve point loading (Power Demand=800MW)

Power output (MW)	NPSOTVAC	PSO
P1	312.7941	265.1040
P2	93.1258	167.8146
P3	135.0088	80.0000
P4	78.6480	86.8141
P5	137.5567	148.9741
P6	42.8666	51.2956
Total cost($/hr)	10052.00	10150.00

Table 11
Power o/p for the six generator units system without considering transmission losses & valve point loading (Power Demand=1200MW)

Power output(MW)	NPSOTVAC	PSO
P1	408.9468	408.5556
P2	134.6869	166.1707
P3	285.3559	267.1401
P4	104.7308	125.5133
P5	178.9869	178.7351
P6	51.2926	58.88525
Total cost($/hr)	**14447.01**	**14457.15**

Table 12
Power o/p for the six generator units system without considering transmission losses & but including valve point loading (Power Demand=1200MW)

Power output(MW)	NPSOTVAC	PSO
P1	407.8014	443.0852
P2	147.9736	127.4128
P3	271.8737	260.0098
P4	117.5628	138.6747
P5	171.2375	153.4433
P6	83.5510	77.3743
Total cost($/hr)	14960.05	15266.00

Table 13
Comparison between NPSOTVAC & PSO for six generating units system without transmission loss & valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
800	9499.20	9533.51
1200	14447.01	14457.15

Table 14
Comparison between NPSOTVAC & PSO for six generating units system without transmission loss but including valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
800	10052.00	10150.00
1200	14960.05	15266.00

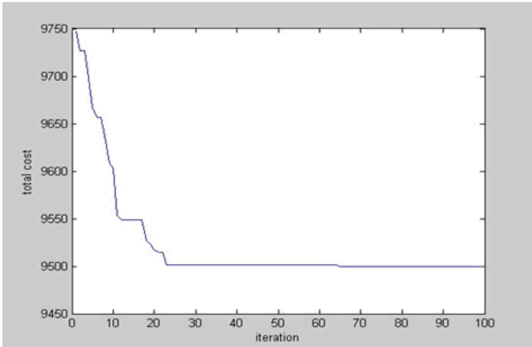

Fig. 10. Graph between No. of iterations & cost in $/hr for load of 800 MW without considering loss & valve point loading effect for 6 generators system using NPSOTVAC converged at 9499.20 $/hr

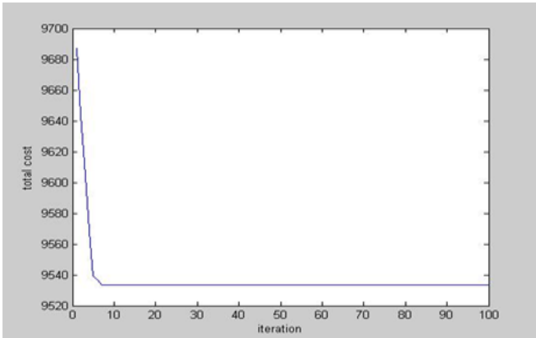

Fig. 11. Graph between No. of iterations & cost in $/hr for load of 800 MW without considering loss & valve point loading effect for 6 generators system using PSO converged at 9533.51 $/hr

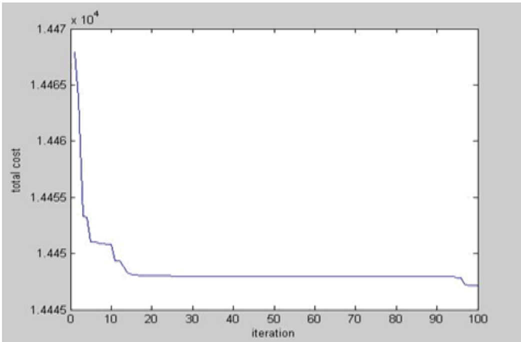

Fig. 12. Graph between no. of iterations & cost in $/hr for load of 1200 MW without considering loss & valve point loading effect for 6 generators system using NPSOTVAC converged at 14447.01$/hr

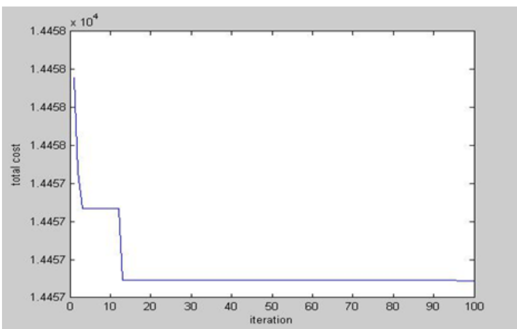

Fig. 13. Graph between No. of iterations & cost in $/hr for load of 1200MW without considering loss & valve point loading effect for 6 generators system using PSO converged at 14457.15 $/hr

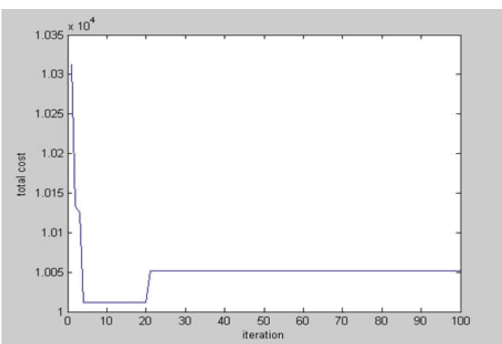

Fig. 14. Graph between No. of iterations & cost in $/hr for load of 800 MW without loss but including valve point loading effect for 6 generators system using NPSOTVAC converged at 10052.00 $/hr

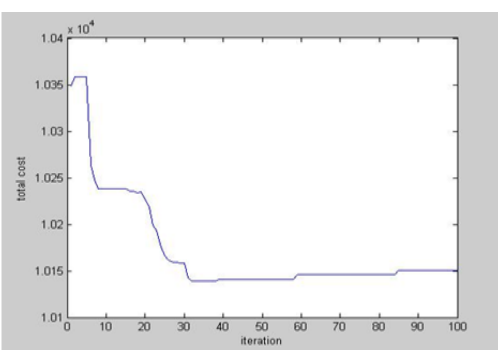

Fig. 15. Graph between No. of iterations & cost in $/hr for load of 800 MW without loss but including valve point loading effect for 6 generators system using PSO converged at 10150.00 $/hr

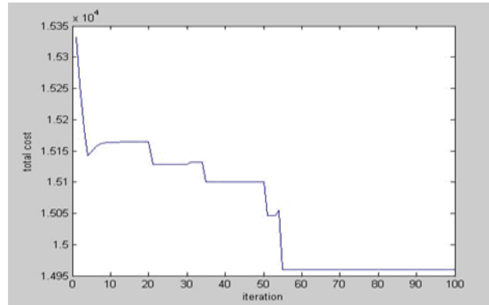

Fig. 16. Graph between No. of iterations & cost in $/hr for load of 1200 MW without loss but including valve point loading effect for 6 generators system using NPSOTVAC converged at 14960.05 $/hr

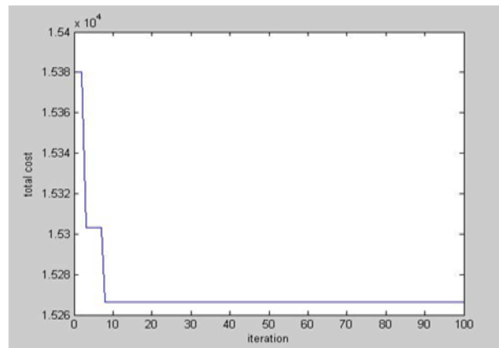

Fig. 17. Graph between No. of iterations & cost in $/hr for load of 1200 MW without loss but including valve point loading effect for 6 generators system using PSO converged at 15266.00 $/hr

C. Case study-3

1) ELD for ten generators system

Optimum Solution Using PSO & NPSOTVAC Algorithm:

The description of the results by utilizing PSO & NPSOTVAC without considering losses is detailed. A system of ten generator units with the effects of PSO & NPSOTVAC Algorithm is studied in this test. Table 16 and 18 gives power output for ten generator units system without considering transmission loss & valve point loading effect for 2000 MW and 2500 MW respectively. Table 17 and 19 gives power output for ten generating units system without transmission loss but including valve point loading effect for 2000 MW and 2500 MW respectively. Table 20 and 21 provides the comparison study of the two methods. Fig. 18 and 19 gives graph between No. of Iterations and Cost in R/hr for load of 2000 MW without considering loss and valve point loading effect of 10 generators system using NPSOTVAC and PSO method respectively. Fig. 20 and 21 gives graph between No. of Iterations and Cost in R/hr for load of 2500 MW without considering loss and valve point loading effect of 10 generators system using NPSOTVAC and PSO method respectively. Fig. 22, 23, 24 and 25 gives same graph but with considering valve point loading effect.

Table 15
Specification for ten generators without loss test system [37]

Gen	ai	bi	ci	di	ei	Pmax	Pmin
P1	.000299	10.1	671	250	.036	455	150
P2	.000183	10.2	574	250	.036	455	150
P3	.001126	8.8	374	100	.081	130	20
P4	.001126	8.8	374	100	.081	130	20
P5	.000205	10.4	461	260	.033	470	150
P6	.000301	10.1	630	255	.034	460	135
P7	.000364	9.8	548	252	.033	465	135
P8	.000338	11.2	227	200	.042	300	60
P9	.000807	11.2	173	110	.070	162	25
P10	.001203	10.7	175	110	.071	160	25

Table 16
Power o/p for the ten generator units system without considering transmission losses & valve point loading (Power Demand=2000MW)

Power output(MW)	NPSOTVAC	PSO
P1	444.6127	227.8469
P2	257.5885	436.5476
P3	74.9806	47.3374
P4	86.0715	87.1901
P5	166.1761	184.2883
P6	315.5905	425.2153
P7	349.8627	420.8406
P8	240.8821	62.6594
P9	25.7388	51.9654
P10	38.4965	56.1090
Total cost($/hr)	24296.00	24481.20

Table 17
Power o/p for the ten generator units system without considering transmission losses & but including valve point loading (Power Demand=2000MW)

Power output(MW)	NPSOTVAC	PSO
P1	365.7064	190.6046
P2	227.6599	228.0666
P3	130.0000	130.0000
P4	101.1339	130.0000
P5	415.2442	258.1498
P6	223.5915	313.5872
P7	401.5430	443.4709
P8	60.7230	64.0929
P9	42.0406	157.6569
P10	32.3574	84.3712
Total cost($/hr)	25377.01	25442.00

Table 18
Power o/p for the ten generator units system without considering transmission losses & valve point loading (Power Demand=2500MW)

Power output(MW)	NPSOTVAC	PSO
P1	372.0340	279.0849
P2	377.6441	453.8403
P3	114.0693	87.5530
P4	92.7842	123.8473
P5	447.0299	441.8662
P6	415.5552	399.8675
P7	344.7687	362.5802
P8	105.4267	134.0770
P9	75.1760	101.4729
P10	155.51148	115.8108
Total cost($/hr)	**29524.00**	**29620.00**

Table 19
Power o/p for the ten generator units system without considering transmission losses & but including valve point loading (Power Demand=2500MW)

Power output(MW)	NPSOTVAC	PSO
P1	430.7305	378.4933
P2	405.1492	333.2706
P3	109.0784	85.9661
P4	102.3622	130.0000
P5	437.7348	392.6143
P6	318.1082	408.3489
P7	239.2733	465.0000
P8	193.6572	170.1768
P9	107.5829	25.0000
P10	156.3233	111.1301
Total cost($/hr)	30590.00	30944.00

Table 20
Comparison between NPSOTVAC & PSO for ten generating units system without transmission loss & valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
2000	24296.00	24481.20
2500	29524.00	29620.00

Table 21
Comparison between NPSOTVAC & PSO for six generating units system without transmission loss but including valve-point loading effect

Load Demand(MW)	NPSOTVAC($/hr)	PSO($/hr)
2000	25377.01	25442.12
2500	30590.00	30944.00

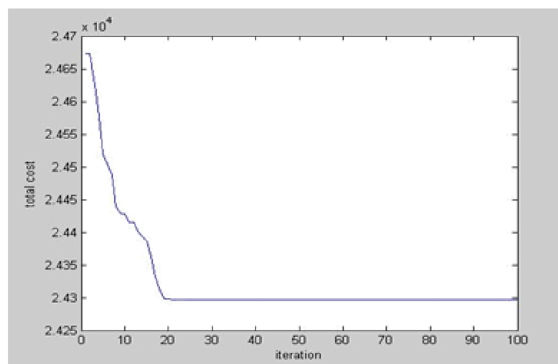

Fig. 18. Graph between No. of iterations & cost in $/hr for load of 2000 MW without considering loss & valve point loading effect for 10 generators system using NPSOTVAC converged at 24296.00 $/hr

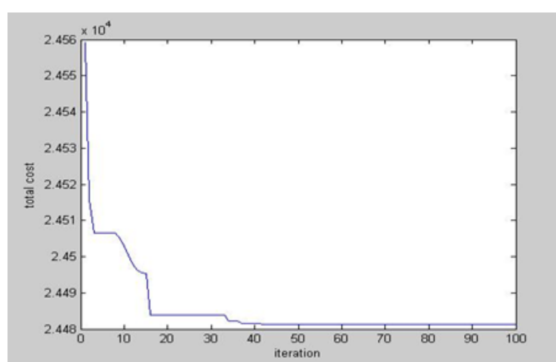

Fig. 19. Graph between No. of iterations & cost in $/hr for load of 2000 MW without considering loss & valve point loading effect for 10 generators system using PSO converged at 24481.20 $/hr

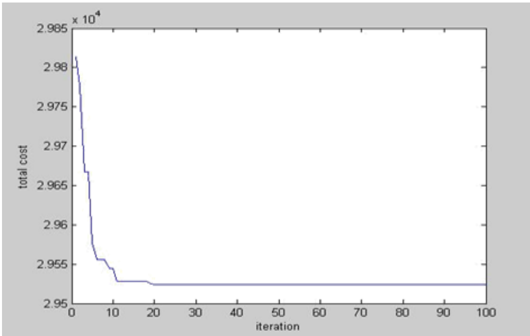

Fig. 20. Graph between No. of iterations & cost in $/hr for load of 2500 MW without considering loss & valve point loading effect for 10 generators system using NPSOTVAC converged at 29524.00 $/hr

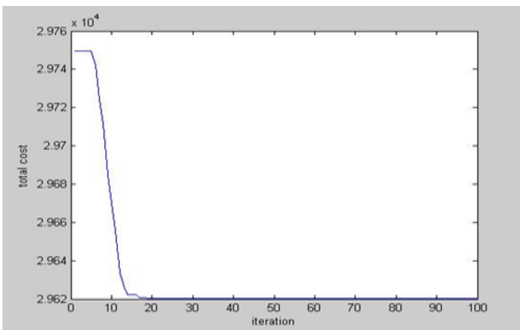

Fig. 21. Graph between No. of iterations & cost in $/hr for load of 2500 MW without considering loss & valve point loading effect for 10 generators system using PSO converged at 29620.00 $/hr

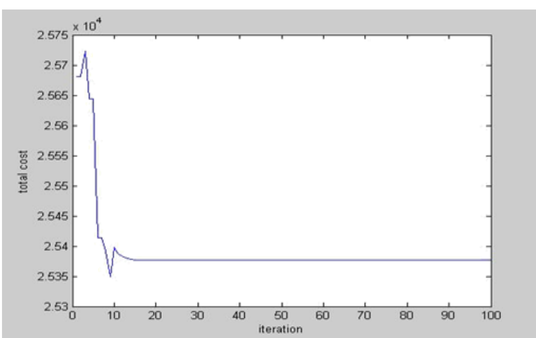

Fig. 22. Graph between No. of iterations & cost in $/hr for load of 2000 MW without loss but including valve point loading effect for 10 generators system using NPSOTVAC converged at 25377.01 $/hr

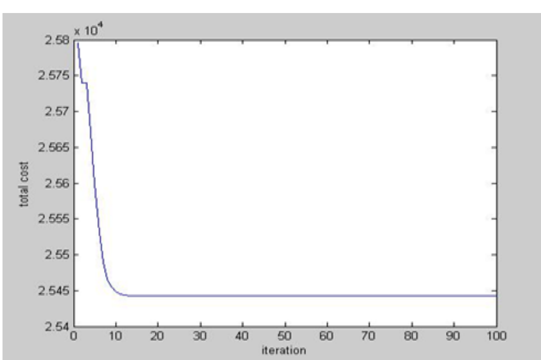

Fig. 23. Graph between No. of iterations & cost in $/hr for load of 2000 MW without loss but including valve point loading effect for 10 generators system using PSO converged at 25442.12 $/hr

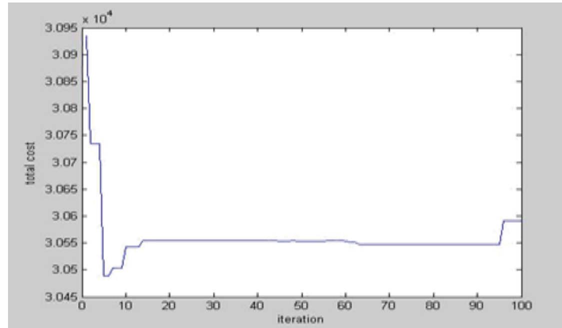

Fig. 24. Graph between No. of iterations & cost in $/hr for load of 2500 MW without loss but including valve point loading effect for 10 generators system using NPSOTVAC converged at 30590.00 $/hr

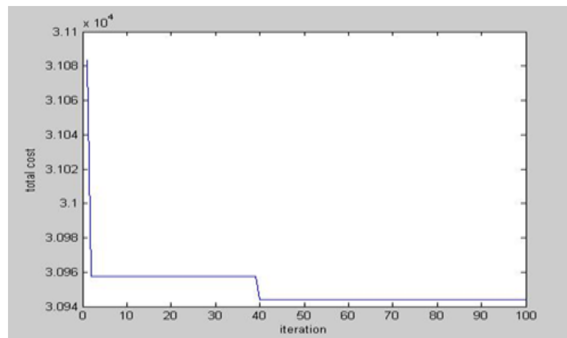

Fig. 25. Graph between no. of iterations & cost in $/hr for load of 2500 MW without loss but including valve point loading effect for 6 generators system using PSO converged at 30944.00 $/hr

6. Conclusion

The economic load problems is to determine the optimal combination of power outputs of all generating units so as to meet the required demand at minimum cost while satisfying the constraints. In this paper PSO and NPSOTVAC is proposed on solving of Economic Load Dispatch problems. The differential evolution algorithm has been successfully implemented to solve ELD problems with the generator constraints as linear equality and inequality constraints and also considering transmission loss. PSO and NPSOTVAC algorithm is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The results clearly show the effectiveness of the method in solving ELD problem.

Economic Load dispatch problem here solved for three different cases. One three units in generating stations, other six units in generating stations and another with ten generators without and with valve point loading effect using PSO and NPSOTVAC algorithm.

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