This paper proposes a particle swarm optimization approach with time varying acceleration coefficients (TVAC_PSO) for an extensive study of the economic dispatch problem with valve point loading (EDVPL). An optimal short-term thermal generation schedule for 24 time intervals has been presented for the same purpose. In this paper, transmission losses and valve-point loading (VPL) have been considered. The VPL effect results in higher order nonlinearities in the input-output characteristics of a generator. For demonstrating the effectiveness of the proposed method two test systems, first one comprising of three generators and the second one comprising of thirteen generators, have been considered. The performance of the proposed method has been compared with various PSO strategies. The results show that the proposed TVAC_PSO strategy provides comparatively better solutions in terms of total fuel cost as compared to other PSO strategies. Also, the global search capability is enhanced and premature convergence is avoided.

**Keywords** Economic Dispatch, Particle Swarm Optimization, Time Varying Acceleration Coefficients, Valve Point Loading

**1. Introduction**

Economic Dispatch (ED) is one of the most important issues in power system operation. The main aim of ED is to minimize the operating cost of units, while satisfying certain constraints [1-3]. Thus, it can be stated that ‘the economic dispatch problem is to define the generation level of each plant so that the total cost of generation and transmission is minimum for a prescribed schedule of loads’ [1]. Certain conventional methods have been developed in the previous years for solving the ED problem. Some of these methods include lambda-iteration method, direct search method, Newton-Raphson method, efficient method [1, 5-7]. In these methods assumption is made that the incremental cost curves of the generators are monotonically increasing piece-wise linear. However, in practical case the cost curves of the generators are highly non-linear and hence, such an assumption may not give accurate results. The nonlinearities in the generator operation are due to valve-point loading effects, prohibited operating zones, etc. [1].

In recent years certain artificial intelligence (AI) techniques such as Fuzzy Logic (FL) [8, 9], Artificial Neural Network (ANN) [10-12], Genetic Algorithm (GA) [13-17], etc. have been successfully applied to the ED problems for units having non-linear cost functions. However, problem faced by FL is its low accuracy and large computational complexity. In ANN adopting an unsuitable sigmoidal function may suffer from excessive numerical iterations, resulting in huge calculations.

GA, which emulates from natural genetic operations, has emerged as a candidate for many optimization problems (including ED) due to its flexibility and efficiency. GA is a stochastic searching algorithm. In some GA applications, certain constraints including network losses and valve-point effects were considered for the practicability of the proposed method. Among these Walters and Sheble [13] presented a GA model for solving the ED problem including valve-point effects. Also Chen and Chang [15] presented a model that included network losses and valve-point effects. For an efficient solution to the ED problem, Chiang [17] and Amjadi and Nasiri-Rad [18] presented improved and real-coded GA models respectively that can obtain high quality solutions in lesser time.

Although the GA model has been employed successfully in various optimization problems, recent researches show some difficulties with its implementation. GA shows quiet a large inefficiency when being implemented to objective functions in which the parameters to be optimized are highly correlated [19]. Also premature convergence is another
problem that reduces its searching capability[20].

Particle swarm optimization (PSO) was developed by Kennedy and Eberhart in 1995 motivated by social behavior of organisms such as fish schooling and bird flocking[21]. It is one of the modern heuristic algorithms and has been found to be efficient and robust in solving non-linear problems[21-23]. The PSO technique can generate high quality solutions taking lesser computational time and providing a faster convergence as compared to other AI techniques[20,24-25,31]. In standard PSO (SPSO)[21], particles move around in the search space with the help of two accelerating components. One component, known as the cognitive component, controls the local exploration of the particles, while the second component, known as the social component, guides the global search capability of the particles. Kennedy and Eberhart[21] have shown that a high value of the local component will result in excessive exploration of the particles through the search space while a high value of the social component will result in a premature convergence of the particles. Various researchers[23,26,32-34] have found that the SPSO quickly finds a good local solution but gets stuck to it for rest of the iterations without a further improvement.

In order to overcome the above problems, a time varying acceleration coefficient[26] PSO (TVAC_PSO) strategy has been employed in this paper. The TVAC_PSO strategy finds a proper balance between the local and the global component and hence, the problem of premature convergence has been overcome to a much greater extent. The performance of the proposed TVAC_PSO strategy has been compared with SPSO[21], New PSO[27] and Anti-predatory PSO[28]. In order to show the superiority of the TVAC_PSO strategy over other strategies two test systems have been taken. The first test system consists of three generating units[13] while the second test system contains thirteen generating units[30]. A 24-hour short-term thermal generation schedule[4] has been presented for the three generator system with a peak demand of 850 MW to further add to the effectiveness of the proposed strategy.

2. Economic Dispatch with Valve-Point Loading (EDVPL)

The input-output characteristics (or cost functions) of a generator are approximated using quadratic or piece-wise quadratic functions, under the assumption that the incremental cost curves of the units are monotonically increasing piece-wise linear functions. However, real input-output characteristics display higher order nonlinearities and discontinuities due to valve point loading (VPL) in fossil fuel burning plants. The valve-point loading effect has been modeled in as a recurring rectified sinusoidal function[1].

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost functions. The valve-point effects introduce ripples in the heat-rate curves. Mathematically, ED problem considering VPL[1] is defined as:

$$F(P_{gl}) = a_i P_{gl}^2 + b_i P_{gl} + c_i + \left|d_i \cdot \sin \left(e_i \cdot \left(P_{gil} - P_{gl}\right)\right)\right|$$  \hspace{1cm} (1)

Where,

- $F(P_{gl})$ is the fuel cost,
- $P_{gl}$ is the active power generated,
- $a_i, b_i, c_i, d_i, e_i$ are the fuel cost coefficients of the $i_{th}$ generator.

The objective of the EDVPL problem is to determine the optimal power output $P_{gl}$ of each of the generators for a total load demand of $P_D$. Total fuel cost $F_{total}$ for NG generators is minimized subject to the equality and the inequality constraints. Hence, the optimization problem can be stated as[1]:

Minimize $F_{total} = \sum_{i=1}^{NG} F(P_{gi})$  \hspace{1cm} (2)

subject to the constraints given as:

a) the equality constraint–

$$\sum_{i=1}^{NG} F(P_{gi}) = P_D + P_L$$  \hspace{1cm} (3.1)

b) the inequality constraint–

$$P_{gil} \leq P_{gi} \leq P_{gimax}$$  \hspace{1cm} (3.2)

The total transmission losses $P_L$ is a function of unit power outputs that can be expressed using B-coefficients as[1]

$$P_L = \sum_{i=1}^{NG} P_i \sum_{j=1}^{NG} B_{ij} P_j + \sum_{i=1}^{NG} P_i B_{0i} + B_{00}$$  \hspace{1cm} (4)

3. Review of Various PSO Strategies

Since the introduction of the PSO, various PSO based strategies have been successfully applied to deal with the ED problems. Some of the PSO strategies applied to the ED problems are presented briefly in this paper and their performances have been compared with the presented TVAC_PSO strategy.

3.1. Standard PSO (SPSO)

SPSO[21], as an optimization tool, provides a population-based search procedure in which individuals called particles change their position(states) with time. In a PSO system, particles fly around in a multi-dimensional search space. During flight, each particle adjusts its position according to its own experience and the experience of neighboring particles, making use of the best position encountered by it and neighbours. The swarm direction of a particle is defined by the set of particles neighbouring the particle and its history experience. Instead of using evolutionary operation to manipulate the individuals, like in other evolutionary computational algorithms, each individual in PSO flies in the search space with a velocity which is dynamically adjusted according to its own flying experience and its companions flying experience. Let $p$ and $v$ denote a particle’s co-ordinate(position) and its corresponding flight speed(velocity) in a search space respectively. Therefore, each $i_{th}$ particle is treated as a volume less particle, represented as $p_i=(p_{i1}, p_{i2}, ..., p_{id})$ in the $d$-dimensional space.
The best previous position of the \( i_{th} \) particle is recorded and represented as \( p_{besti} = (p_{best1}, p_{best2}, \ldots, p_{bestd}) \). The index of the best particle among all the particles is treated as global best particle, is represented as \( g_{best} \). The velocity for the \( i_{th} \) particle is represented as \( v_i = (v_{i1}, v_{i2}, \ldots, v_{id}) \).

The modified velocity and position of each particle can be calculated using the current velocity and the distance from \( p_{besti} \) to \( g_{best} \) as shown in the following formulas,

\[
v_{id}^{(t+1)} = v_{id}^{t} + p_{w} \cdot c_1 \cdot \text{rand1}(\cdot) \cdot (p_{bestid} - p_{id}) + c_2 \cdot \text{rand2}(\cdot) \cdot (g_{bestid} - p_{id}) \quad (5)
\]

\[
p_{id}^{(t+1)} = p_{id}^{t} + v_{id}^{(t+1)} \quad (6)
\]

In the above equation, \( c_1 \) and \( c_2 \) are known as the acceleration coefficients that pull each particle towards the \( p_{best} \) and \( g_{best} \) positions. \( \text{Rand}(\cdot) \) and \( \text{rand}(\cdot) \) are the uniform random numbers between [0,1]. The term \( \text{rand1}(\cdot) \cdot (p_{bestid} - p_{id}) \) is called the social component. The term \( \text{rand2}(\cdot) \cdot (g_{bestid} - p_{id}) \) is called the cognitive component. The equation updates the PSO model is given by:

\[
v_{id}^{(t+1)} = v_{id}^{t} + p_{w} \cdot c_1 \cdot \text{rand1}(\cdot) \cdot (p_{bestid} - p_{id}) + c_2 \cdot \text{rand2}(\cdot) \cdot (g_{bestid} - p_{worstid}) + c_2 \cdot \text{rand1}(\cdot) \cdot (g_{bestid} - p_{id}) + c_2 \cdot \text{rand2}(\cdot) \cdot (p_{id} - g_{worstid}) \quad (9)
\]

where \( g_{worst} \) is the global worst position of member \( d \) until iteration \( t \). The acceleration coefficient \( c_2 \) helps the particles to accelerate towards their previous global best positions and \( c_2 \) helps the particles to move away from their previous worst positions. By using the bad experiences, particle always by-passes its previous worst positions. Hence, exploration capability is further enhanced.

### 3.3. Anti-predatory PSO (APSO)

Another PSO variant proposed by Selvakumar and Thanushkodi[28] included an anti-predatory property. The anti-predatory property, which is natural among particles, helps the swarm escape from the predators. This strategy models the predators as the worst result points and the new model is named anti-predatory PSO. The APSO is developed by splitting both the cognitive and the social behaviours of the SPSO. Here, along with the cognitive component, the social component is also split into global good experience and global bad experience components. The velocity update equation of the APSO model is given by:

\[
v_{id}^{(t+1)} = v_{id}^{t} + p_{w} \cdot c_1 \cdot \text{rand1}(\cdot) \cdot (p_{bestid} - p_{id}) + c_2 \cdot \text{rand2}(\cdot) \cdot (g_{bestid} - p_{id}) + c_2 \cdot \text{rand1}(\cdot) \cdot (g_{bestid} - p_{id}) + c_2 \cdot \text{rand2}(\cdot) \cdot (p_{id} - g_{worstid}) \quad (9)
\]

Here, \( g_{worst} \) is the global worst position of member \( d \) until iteration \( t \). The acceleration coefficient \( c_2 \) helps the particles to accelerate towards their previous global best positions and \( c_2 \) helps the particles to move away from their previous worst positions. By using the bad experiences, particle always by-passes its previous worst positions. Hence, exploration capability is further enhanced.

### 4. Proposed PSO strategy

#### 4.1. PSO with Time-varying Acceleration Coefficients (TVAC PSO)

In this paper, the TVAC_PSO[26] strategy has been used to solve the EDVPL problems. Basic purpose of using the time varying acceleration coefficients is to improve the global exploration in the early part of the process and to enhance the convergence of the particles in the later stages of the process. This is done by varying the acceleration coefficients \( c_1 \) and \( c_2 \) with time in such a manner that the cognitive component reduces and the social component increases as iterations increase. In short, it can be stated that a large cognitive component and a small social component at the beginning of the process help the particles to explore the search space in a better way while a smaller cognitive component and a larger social component at later stages of the process allow the particles to converge to the global optima. The time varying acceleration coefficients are given as[29]:

\[
c_1 = (c_{1f} - c_{1i}) \cdot \left(\frac{lt}{lt_{max}}\right) + c_{1i}
\]

\[
c_2 = (c_{2f} - c_{2i}) \cdot \left(\frac{lt}{lt_{max}}\right) + c_{2i}
\]

Where \( c_{1i}, c_{1f}, c_{2i} \) and \( c_{2f} \) are initial and final values of the cognitive and social acceleration coefficients respectively.

#### 4.2. Algorithm for TVAC PSO

The sequential steps of the proposed TVAC PSO strategy are given below.
Step1: Representation of the swarm- Since the decision variables of the economic dispatch problem are the real power generations, they are used to form the swarm. The set of real power output\((P_g)\) of all the generators is represented as the position of the particle in the swarm. For a system with \(NG\) generators, the particle position is represented as a vector of length \(NG\). If there are \(NP\) particles in the swarm, the complete swarm is represented as a matrix as shown below:

\[
\begin{pmatrix}
P_{11} & P_{12} & \cdots & P_{1NG} \\
P_{21} & P_{22} & \cdots & P_{2NG} \\
\vdots & \vdots & \ddots & \vdots \\
P_{NP1} & P_{NP2} & \cdots & P_{NPNG}
\end{pmatrix}
\]

Where \(P_{ij}\) is the \(j\)th position component of particle \(i\) and it represents the real power generation of generator \(j\) of the possible solution \(i\).

Step2: Initialization of the swarm- The particles of the swarm are initialized randomly according to the limit of each generating unit. These initial particles must be feasible candidate solutions that must satisfy the operating constraints.

Step3: Evaluation of objective function- In order to satisfy the equality constraint(3), a generator is arbitrarily selected as a dependent generator\(P_{dep}\) whose generation is calculated as given below:

\[
P_{dep} = (P_D - \sum_{i=1}^{NG} P_{gi} \quad \text{if } P_L \neq 0 \quad (12.1)(P_D) - \sum_{i=1}^{NG} P_{gi} \quad \text{if } P_L = 0(12.2)
\]

If the output of the dependent generator violates its lower limit, its output is set equal to its lower limit and if it violates its upper limit, its output is set equal to its upper limit. An output between the lower and upper limit is automatically acceptable.

The operating cost of individual generating unit is calculated using(1) and hence the total operating cost can be calculated using(2).

Step4: Initialization of best positions- In the PSO strategy, the particle’s best position, \(p_{bestid}\) and global best position, \(g_{bestd}\) are the key factors. The position with minimum objective function value is the particle’s best position. The best position out of all the \(p_{bestid}\) is taken as \(g_{bestd}\).

Step5: Movement of the particles- Particles in the swarm are accelerated to new positions by adding new velocities to their current positions. The new velocity is calculated using the equation:

\[
v_{id}^{t+1} = v_{id}^{t} + (c_1(v_{id}^{t} - p_{id}^{t}) + c_2(v_{d poorest} - p_{id}^{t}) + c_3(v_{d random} - p_{id}^{t}))\]

The positions of the particles are updated using(6).

Step6: Updating the best positions- If the evaluation value of each particle is better than previous \(p_{bestid}\), the current value is set to \(p_{bestid}\). If the best \(p_{bestid}\) is better than \(g_{bestd}\), this new value is set as \(g_{bestd}\). An objective function value at \(g_{bestd}\) is set as \(F_{best}\).

Step7: Stopping criterion- If the number of iterations reaches the maximum than the process is stopped and \(F_{best}\) is the minimum generation cost of the economic dispatch problem. Otherwise, the above process is repeated from step2.

### 5. Test Systems and Results

In order to show the superiority of the TVAC_PSO strategy over other PSO strategies discussed before, two test systems have been taken into consideration. The first test system consists of three generating units\([13]\) with a load demand of 850 MW. The second test system has been taken from\([30]\) which consist of 13 generating units with a load demand of 1800 MW. In this paper following parameters have been used for different PSO strategies: For NPSO, \(c_1 = 1.6, c_2 = 0.4\) and \(c_3 = 2\)\([27]\) have been used. For APSO, \(c_1 = 1.6, c_2 = 0.4, c_3 = 1.8\) and \(c_3 = 0.2\)\([28]\) have been adopted.

For TVAC_PSO, \([26]\) suggests that the values for \(c_1\) should vary from 2.5 to 0.5 and from 0.5 to 2.5 in case of \(c_2\) for best results.

#### Case 1: Three-Generator system

For this system a population size of 20 has been taken with maximum number of iterations as 200. Losses have also been calculated using the loss coefficients given in\([13]\) by using equation(4). Power generation of each generator, generating cost and losses corresponding to different PSO strategies have been shown in table 1. Convergence characteristics of each PSO model are shown in figure 1.

| Power output(MW) | SPSEO | NPSO | APSO | TVAC_PSO |
|------------------|-------|------|------|-----------|
| P1               | 399.3723 | 399.8393 | 400.4504 | 399.1669 |
| P2               | 325.7694 | 326.5124 | 326.1388 | 326.8991 |
| P3               | 150.6753 | 149.4418 | 149.1996 | 149.7331 |
| Losses(MW)       | 25.8170 | 25.7936 | 25.7890 | 25.7991 |
| Cost($)          | 8453.6077 | 8449.3794 | 8443.5561 | 8440.7647 |

![Comparison of various PSO strategies for a 3 gen system](image)

**Figure 1.** Convergence characteristics of different PSO strategies(3-generator system)
Table 2. Optimal results for 13 generator system excluding losses ($P_d = 1800$ MW)

| Power output (MW) | SPSO  | NPSO  | APSO  | TVAC_PSO |
|-------------------|-------|-------|-------|----------|
| P1                | 538.5587 | 538.5042 | 539.1930 | 628.3185 |
| P2                | 149.5459 | 298.7765 | 297.6252 | 223.5256 |
| P3                | 224.3200 | 301.2419 | 312.2458 | 298.4228 |
| P4                | 154.8511 | 60.0310  | 60.0280  | 60.0000  |
| P5                | 109.8372 | 60.0000  | 60.0000  | 60.0000  |
| P6                | 109.2508 | 60.0000  | 60.0000  | 60.0000  |
| P7                | 60.0000  | 60.0120  | 60.0000  | 60.0000  |
| P8                | 60.0000  | 60.0000  | 60.0000  | 60.1560  |
| P9                | 60.0000  | 106.4773 | 160.7820 | 159.5771 |
| P10               | 113.0114 | 40.1120  | 40.1050  | 40.0000  |
| P11               | 73.2248  | 40.0000  | 40.0000  | 40.0000  |
| P12               | 92.3999  | 55.2250  | 55.0210  | 55.0000  |
| P13               | 55.0000  | 119.6200 | 55.0000  | 55.0000  |
| Cost($/hr)         | 18156.0423 | 18133.1781 | 18105.7977 | 17989.0048 |

Table 3. Short-term thermal generation scheduling for case 1 (Peak Demand = 850 MW)

| Time interval | Demand (MW) | P1 (MW) | P2 (MW) | P3 (MW) | Generation Cost ($/hr) | Losses (MW) |
|---------------|-------------|---------|---------|---------|------------------------|-------------|
| 1             | 490         | 299.4235 | 165.8151 | 50.0000 | 5299.7132              | 23.8842     |
| 2             | 493         | 299.3172 | 167.5672 | 50.0000 | 5301.7452              | 23.8843     |
| 3             | 495         | 299.4662 | 169.4179 | 50.0003 | 5302.2856              | 23.8844     |
| 4             | 499         | 299.4661 | 173.1361 | 50.2878 | 5308.0231              | 23.8900     |
| 5             | 506         | 299.4662 | 180.0012 | 50.4255 | 5410.2912              | 23.8929     |
| 6             | 513         | 299.4676 | 187.4176 | 50.0000 | 5524.1834              | 23.8852     |
| 7             | 537         | 299.4662 | 174.7272 | 87.4010 | 5731.8712              | 24.5944     |
| 8             | 588         | 299.4662 | 175.3221 | 138.7424 | 6186.6227              | 25.5710     |
| 9             | 605         | 299.6675 | 181.3801 | 149.7331 | 6303.0091              | 25.7808     |
| 10            | 651         | 299.7988 | 177.9412 | 200.0000 | 6724.9173              | 26.7408     |
| 11            | 699         | 399.1993 | 175.7951 | 149.7962 | 7093.7716              | 25.7962     |
| 12            | 755         | 399.2602 | 182.4889 | 200.0000 | 7685.5134              | 26.7491     |
| 13            | 793         | 399.1993 | 262.4881 | 157.2503 | 8077.7387              | 25.9377     |
| 14            | 812         | 399.4145 | 324.7318 | 112.9521 | 8186.1096              | 25.0984     |
| 15            | 831         | 399.1993 | 312.8684 | 149.7303 | 8399.4645              | 25.7979     |
| 16            | 850         | 399.1669 | 326.8991 | 149.7331 | 8440.7647              | 25.7991     |
| 17            | 824         | 399.1407 | 251.6786 | 199.9326 | 8229.0647              | 26.7519     |
| 18            | 756         | 306.7987 | 325.2584 | 149.7331 | 7650.0912              | 25.7901     |
| 19            | 809         | 399.1993 | 323.1519 | 111.7237 | 8161.6756              | 25.0749     |
| 20            | 688         | 298.5953 | 314.3775 | 99.8666  | 7047.5423              | 24.8393     |
| 21            | 625         | 299.8796 | 250.4649 | 99.4834  | 6407.7079              | 24.8279     |
| 22            | 540         | 299.4893 | 173.9640 | 91.2135  | 5737.5865              | 24.6668     |
| 23            | 495         | 299.4662 | 169.4179 | 50.0003  | 5302.2534              | 23.8844     |
| 24            | 490         | 299.4235 | 165.1851 | 50.0000  | 5299.7175              | 23.8842     |

Case 2: Thirteen-Generator system

For this system population size has been taken as 30 and maximum number of iterations as 200. Losses have been neglected for this case. Power generation of each unit and generating cost are shown in Table 2. Corresponding convergence characteristics are shown in Figure 2.

The effectiveness of the proposed TVAC_PSO strategy has been demonstrated with the help of the above two test
systems. The optimal generation costs for the three-generator system and the thirteen-generator system using TVAC_PSO are $8440.7647 per hour (shown in bold in table 1) and $17989.0048 per hour (shown in bold in table 2) respectively which are lower as compared to the other PSO strategies discussed. The cost convergence characteristics for the three-generator system and the thirteen-generator system have been shown in figures 1 and 2 respectively. From these it can be easily deduced that the proposed TVAC_PSO strategy is better as compared to other PSO strategies. The TVAC_PSO strategy for the three-generator system has been used for finding the optimal short-term generation schedule for 24 time intervals each of 1 hour[4] with a peak demand of 850 MW. The optimal generation schedule has been shown in table 3. Load profile during 24 time intervals is shown in figure 3.

6. Conclusions

In this paper, the TVAC_PSO strategy has been applied to EDVPL problems. A 24-hour short-term thermal generation scheduling has been presented to further add to the effectiveness of the proposed strategy. The performance of this strategy has been compared with SPSO, NPSO and APSO. Two standard test systems have been used for comparison. It has been found that by using the time varying acceleration coefficients better results are obtained in respect with the generation cost. The TVAC help in avoiding the premature convergence and thus providing a stable convergence. The TVAC_PSO strategy outperforms other PSO strategies, particularly for EDVPL problems, in terms of solution quality, stable convergence and stability.

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