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Application of Particle Swarm Optimization Algorithm to Optimal Economic Load Dispatch: A Case Study of the Western Libyan Power System

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تطبيق خوارزمية تحسين سرب الجسيمات علي التوزيع الأمثل للأحمال الاقتصادية دراسة حالة لنظام الطاقة في غرب ليبيا

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Abstract:

Economic Load Dispatch (ELD) is a fundamental optimization problem in power system operation that aims to minimize the total fuel cost of electricity generation while satisfying system constraints such as power balance and generator operating limits. Due to the nonlinear and nonconvex nature of practical power systems, classical optimization techniques often fail to provide optimal and reliable solutions. In this paper, the Particle Swarm Optimization (PSO) algorithm is applied to solve the optimal economic load dispatch problem of the Western Libyan Power System. The proposed approach models generator fuel cost functions as quadratic equations and incorporates essential operational constraints. Several simulation scenarios with different load levels are investigated to evaluate the performance of the PSO algorithm. The results demonstrate that PSO effectively achieves minimum fuel cost while maintaining system constraints, showing fast convergence and robust performance. The study confirms that PSO is a suitable and efficient metaheuristic technique for solving complex economic load dispatch problems in real power systems, particularly under realistic operating conditions of the Libyan power grid.

Keywords: Economic Load Dispatch, Power System, Particle Swarm Optimization, Fuel Cost.

الملخص

يُعد التوزيع الاقتصادي للأحمال من أهم مسائل التحسين في تشغيل أنظمة القدرة الكهربائية، إذ يهدف إلى تقليل التكلفة الكلية لوقود توليد الطاقة الكهربائية مع الالتزام بقيود النظام المختلفة، مثل توازن القدرة وحدود تشغيل وحدات التوليد. ونظرًا للطبيعة غير الخطية وغير المحدبة لأنظمة القدرة العملية، فإن تقنيات التحسين التقليدية غالبًا ما تفشل في توفير حلول مثلى وموثوقة. في هذه الورقة، تم تطبيق خوارزمية سرب الجسيمات لحل مسألة التوزيع الاقتصادي الأمثل للأحمال في منظومة القدرة الكهربائية للمنطقة الغربية في ليبيا. تعتمد الطريقة المقترحة على نمذجة دوال تكلفة الوقود لوحدات التوليد على شكل

معادلات تربيعية، مع تضمين القيود التشغيلية الأساسية للنظام. تم دراسة عدة سيناريوهات محاكاة عند مستويات تحميل مختلفة لتقييم أداء خوارزمية PSO أظهرت النتائج أن خوارزمية PSO قادرة على تحقيق الحد الأدنى لتكلفة الوقود مع الحفاظ على جميع قيود النظام، إضافة إلى تمتعها بسرعة تقارب عالية وأداء مستقر وموثوق. وتؤكد هذه الدراسة أن خوارزمية سرب الجسيمات تُعد تقنية تحسين ميتاهيوريستية مناسبة وفعّالة لحل مسائل التوزيع الاقتصادي المعقدة للأحمال في أنظمة القدرة الكهربائية الواقعية، ولا سيما في ظل ظروف التشغيل الفعلية لشبكة الكهرباء الليبية.

الكلمات المفتاحية: التوزيع الاقتصادي للأحمال، أنظمة القدرة، تحسين سرب الجسيمات، تكلفة الوقود.

1-Introduction

Economic Load Dispatch (ELD) is the most basic and deeply investigated power system operation optimization problem. The main purpose of ELD is to find the best generation of a group of committed generating units such that the total fuel cost for electric power production is minimized and all operational and system constraints are maintained. These restrictions usually consist of such things as the power balance restraint, generator operating envelope limits (minimum and maximum), and in realistic power systems transmission losses and other operational restrictions [1].

The significance of the ELD problem is directly connected with its influence on economic performance and operational efficiency of power systems. Even small changes in dispatch methods can lead to significant fuel savings and operational cost reductions when maintained over the lifetime of system operation [2]. Therefore, ELD has been one of the most important issues in power system optimization for a long time.

Classical optimization methods like lambda-iteration method, gradient-based algorithms and linear programming techniques are used to solve the ELD problem in earlier years. These techniques are often successful in practice when the fuel cost functions are smooth, convex and differentiable. However, it is also worth noting that the actual power system can be quite nonlinear nonconvex because of the valve-point loading effects, prohibited operating zones, multi-fuel alternatives, and ramp-rate constraints of generating units [3].

As the scale and complexity of the power grid continue to grow, traditional optimization methods have increasingly revealed their deficiencies. The ELD problem is becoming increasingly complex due to the inclusion of different types of generation units, load variations and more rigorous operational constraints. For this reason, many researchers have resorted to sophisticated optimization approaches that are better-suited for the optimization of nonlinear, nonconvex and large-scale problems [4].

Metaheuristic optimization algorithms have been the applied as competitive options to tackle ELD problem. Such algorithms, inspired from the natural phenomena are gradient free and well suited for complex optimization problems. Genetic Algorithms (GA) [5], Differential Evolution (DE) [6], Ant Colony Optimization (ACO) [7], Artificial Bee Colony (ABC) [8] and Particle Swarm Optimization [9] are among the most investigated metaheuristic algorithms.

system optimization problems. showed the superiority of PSO in an optimal power flow (OPF) compared to other evolutionary algorithms, as well as its robustness and convergence speed [10]. studied the use of PSO for constrained economic dispatch and found better solutions than traditional methods [11]. Later works supported the effectiveness of PSO in solving complex ELD which includes valve-point effect, multiple fuel type availability and wheeling losses [12].

The Libyan power sector, especially in the western part of the country suffers from serious operational and economic problems. These issues include increasing demand for electricity, old infrastructure of generation facilities and fuel supply restrictions and shortcomings in the transmission network. The above conditions require the introduction of optimization methods that are efficient and reliable to improve the economic operation of power grid [13]. However, a literature investigation indicates the absence of studies considering new metaheuristic techniques such as PSO on Libyan power system with realistic operate in data.

The gap motivates this work in which we employ the Particle Swarm Optimization algorithm to solve Optimal economic load Dispatch problem for the WLPSS. Through the assessment of practical generator features and operational constraints, this paper will also attempt to determine the viability of PSO in minimizing fuel costs as well as enhancing dispatch efficiency under real operating circumstances.

2. Problem Formulation of Economic Load Dispatch.

The economic load dispatch (ELD) problem can be expressed as a constrained optimization problem based on the power flow solution of the power system to determine the optimal active generation per unit in a network. This solution minimizes the cost of electricity generation for the entire time horizon, subject to a number of equality and inequality constraints that ensure system is secure and reliable. In real power systems, ELD is not that simple because the generator cost functions are nonlinear and may have some operational bounds or network constraints [14].

2.1 Objective Function (Fuel Cost Minimization).

The Economic Load Dispatch problem goal is to minimize the total fuel cost of all generators fulfilling the system demand. For a power system with N thermal generating units, the total fuel cost function is generally defined as a sum of generator cost functions; generators cost curves are typically considered to be quadratic [15]:

$$FT = min \sum_{i=1}^{n} F_i(P_I) \qquad (1)$$

Where:

- FT is the total cost of generation .
- F_i is the fuel cost function of the $\mathrm{i-th}$ generating unit .
- P_i is the real power output of the $\mathrm{i-th}$ generating unit (MW).

The fuel cost function of each generating unit is typically modeled as a quadratic function of power output:

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

where a_i , b_i ,c_i are the fuel cost coefficients of the $\mathrm{i-th}$ generating unit.

This quadratic model form is a reasonable approximation of generator fuel cost characteristics at typical operating conditions and is one that has been extensively used in ELD literature. But even this simplified model gives rise to a nonlinear optimization problem, that becomes even more complicated when jointed with system constraints. In practice, more nonlinearities such as VPLE (Valve-Point Loading Effects) and various fuels can complicate the objective function [16].

2.2 Power Balance Constraint

The most basic constraint of an ELD problem is the power balance constraint, which makes certain that total generation equals load demand and transmission loss in the system. This constraint is written as an equality:

$$\sum P_I = P_L + P_D \qquad (3)$$

where:

- P_D is the total system load demand (MW),
- P_L represents the total transmission power losses (MW).
- In an idealized lossless system, transmission losses are neglected, and the power balance constraint simplifies to:

The balance constraint on power is important for keeping the system frequency and stable operation of the system. If generation and demand do not match, system frequency deviation can result and cause the system to become unstable. Thus, proper modelling of this constraint is important in realistic ELD solutions.

2.3 Generator Operating Limits

All generating units in a power system are placed with some physical and operational limitations on the range of its active power generation. The limitations are formulated in ELD through inequality constraints:

$$P_{i\,min} \leq P_i \leq P_{i\,max} \qquad (4)$$

Where $P_{i\,max}$ and $P_{i\,min}$ are the maximum and minimum generation limits on ith unit respectively.

In practical power systems, the generator limits determine an important structure that affects the feasible solutions space of ELD problem. Tight operating limits have a potential to induce severe dispatch constraints and consequently the optimization problem becomes more complicated with other constraints such as ramp-rate limits and forbidden zones of operation [17].

2.4 Transmission Losses

In a typical grid system, some power generated is lost in transmitting from the point of generation through the network to your home and business, because of resistance in the wires. These transmission losses should be considered in the ELD model to maintain both realistic and cost-effective dispatch decisions.

A popular method for incorporating the transmission losses in a new model is surge impedance loading factor (B-coefficients), which models the transmission losses as a quadratic function of generator outputs [18]:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i P_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \quad (5)$$

Where P_j are the power generation of $j-th$ units and P_{ij} , B_{0i} , B_{00} are the B – *loss* coefficients

3. Particle Swarm Optimization Algorithm

3.1 Overview of PSO

Particle Swarm Optimization (PSO) is a population-based stochastic optimization algorithm inspired from the social behaviors of bird flocking and fish schooling. PSO sets a swarm of particles (the candidate solution) on exploring the search space cooperatively every particle changes its position based on its own best-know, position as well as the best-known calculated by the entire prevails in a given step. The approach was first introduced by Kennedy and Eberhart, and has been popularly applied as a nature-inspired method in engineering optimization tasks because of its conceptual simplicity and empirical success ever since [19].

The PSO has been thoroughly investigated, theoretically (stability and convergence's results) and experimentally (applications in a wide range of areas). A few improvements and modifications have been suggested to accelerate convergence rates, prevent early convergence, and address constrained or multimodal problems. Guiding theoretical frameworks (e.g., stability analysis and parameter regimes), as well as empirical standards, inform the knowledge of how to design methods, including choice of parameters [20].

The reasons for choosing PSO are its low number of algorithmic operators (no crossover/mutation as in GA), ease of implementation, few controllable parameters and competitive performance on continuous, nonsmooth and multimodal function minima which makes it appealing to solve the Economic Load Dispatch (ELD) problem. These advantages have been validated by empirical studies that specialize PSO for ELD and optimal power flow (OPF)along with power systems settings [21].

3.2 Mathematical Model of PSO

The position and velocity vectors of the particle of a d dimensional search space can be represented as $X_i = (X_{i1} + X_{i2}, \ldots . X_{id})$ and $V_i = (V_{i1} + V_{i2}, \ldots . V_{id})$, respectively. On the basis of the value of the evaluation function, the best previous position of a particle is recorded and represented as $P_{besti=}(p_{i1} + p_{i2}, \ldots . p_{id})$. If the gth particle is the best among all particles in the group so far, it is represented as $P_{besti=}G - besti(p_{g1} + p_{g2}, \ldots . p_{gd})$.The particle tries to modify its position using the current velocity and the distance from pbest and gbest. The modified velocity and position of each particle for fitness evaluation in the next, that is, (k +1)th iteration, are calculated using following equations:

$$V_{id}^{(K+1)} = [W^{*}V_{id}^{K} + {}_{C1}{}^{*}Rand_1(\,)^{*}(P_{besti} - X_{id}^{K}) \quad (6)$$

$$+ {}_{C2}{}^{*}Rand_2(\,)^{*}\left(G_{best\,gd} - X_{id}^{K}\right)] \quad (7)$$

$$X_{id}^{(k+1)} = X_{id}^{k} + V_{id}^{k+1} \quad (8)$$

where W is the inertia weight parameter which controls the global and local exploration capabilities of the particle. c1and c2 are cognitive and social coefficients, respectively, and Rand1(), Rand2() are random numbers between 0 and 1. c1pulls the particles towards local best position and c2 pulls towards the global best position. Usually, these parameters are selected in the range of 0 to 4 [22-24].

4- Simulation Results and Discussion

This section presents the simulation results obtained by applying the Particle Swarm Optimization (PSO) algorithm to the Optimal Economic Load Dispatch (OELD) problem of the Western Libyan Power System. The performance of the proposed approach is evaluated under two operating scenarios with different generation unit configurations and fuel types. All simulations are conducted under steady-state conditions while satisfying power balance and generator operating constraints. The objective is to minimize the total fuel cost, and the convergence behavior and economic performance of the PSO algorithm are assessed.

Case 1: Light fuel Generation Units

In the first scenario, three gas-fired generating units—Al-Khoms, South Tripoli, and Al-Zawiya—are considered. These units exhibit lower fuel cost coefficients and smoother cost characteristics compared to oil-fired units, making them suitable for economic dispatch analysis.

The fuel consumption of each generating unit is modeled using a quadratic relationship between the active power output P (MW) and the thermal fuel input rate $H(P)$ (MBtu/h), which is widely adopted in ELD studies [25]. Using the higher heating value (HHV) of natural light fuel, the fuel price is converted to Dr/MBtu to ensure unit consistency. The fuel cost function is then obtained by multiplying the heat rate equation by the converted fuel price, resulting in a quadratic hourly fuel cost function [26]. given by the following equations.

$$F_1 = (0.1551P^2 + 7.363P + 2731)\ Dr/h \quad (9)$$

$$F_2 = (0.0424P^2 + 26.12P + 1038.6) Dr/h \quad (10)$$

$$F_3 = (0.00491P^2 + 32.37P + 1339.3) Dr/h \quad (11)$$

Only active power constraints are considered. The minimum and maximum operating limits of each generating unit are different, reflecting their technical characteristics. The operating ranges of the generating units were obtained from the General Electricity Company of Libya (GECOL) [27].

$$100(MW) \le P \le 40(MW) \quad (12)$$

$$90(MW) \le P \le 50(MW) \quad (13)$$

$$100(MW) \le P \le 60(MW) \quad (14)$$

The load pattern for the given test system is [160, 180, 200].

As listed in Table 1, the optimal power generation obtained using the Particle Swarm Optimization (PSO) algorithm for three different load levels is summarized as follows. For the first load condition, the optimal generation schedule was 48.6131 MW, 50.0379 MW, and 61.3489 MW for generators 1, 2, and 3, respectively, resulting in a minimum fuel cost of 9,354 DrLY.

When the load demand increased to the second level, the PSO algorithm adjusted the generation outputs to 69.98 MW, 50.0348 MW, and 60 MW. This redistribution of power among the generating units led to a higher minimum operating cost of 9,756 DrLY due to the increased demand.

For the highest load level, the optimal power outputs further increased to 73.69 MW, 66.31 MW, and 60.00 MW for the three generators. Consequently, the minimum fuel cost rose to 10,372 DrLY, which is consistent with the quadratic nature of the fuel cost functions.

Overall, the results demonstrate that the PSO algorithm successfully satisfies the power balance constraint while minimizing the total fuel cost. The smooth variation in generation levels and operating cost confirms the robustness and effectiveness of PSO in solving the economic load dispatch problem.

Table 1 the optimal power generation using (PSO)

Total (MW)	Generator 1 (MW)	Generator 2 (MW)	Generator 3 (MW)	Fuel Cost
160	48.6131	50.0379	61.3489	9251
180	69.98	50.0348	60	9756
200	59.1512	50.0002	90.8486	10480

As illustrated in Figure 1, the convergence curves show the performance of the Particle Swarm Optimization (PSO) algorithm for the three load levels. The total fuel cost decreases sharply during the initial iterations, indicating the fast convergence capability of the algorithm. After a limited number of iterations, the curves become nearly flat, demonstrating that the algorithm has reached stable optimal solutions.

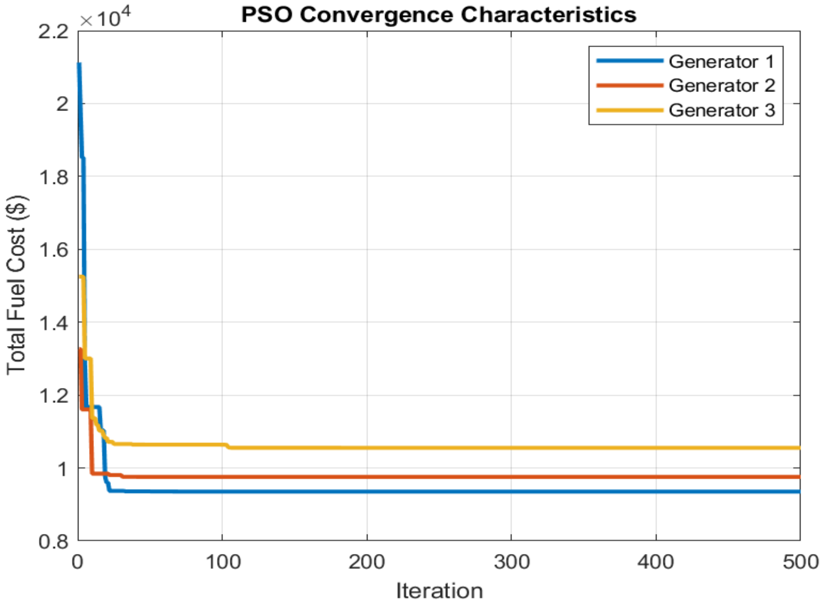

Figure 1: The convergence curves

As shown in Figure 2, the PSO algorithm determines the optimal power output of each generating unit for different load levels. The results indicate that the load is economically shared among the generators while respecting their operating limits. The variation in generation levels reflects the cost characteristics of each unit, where lower-cost generators contribute more to the total demand.

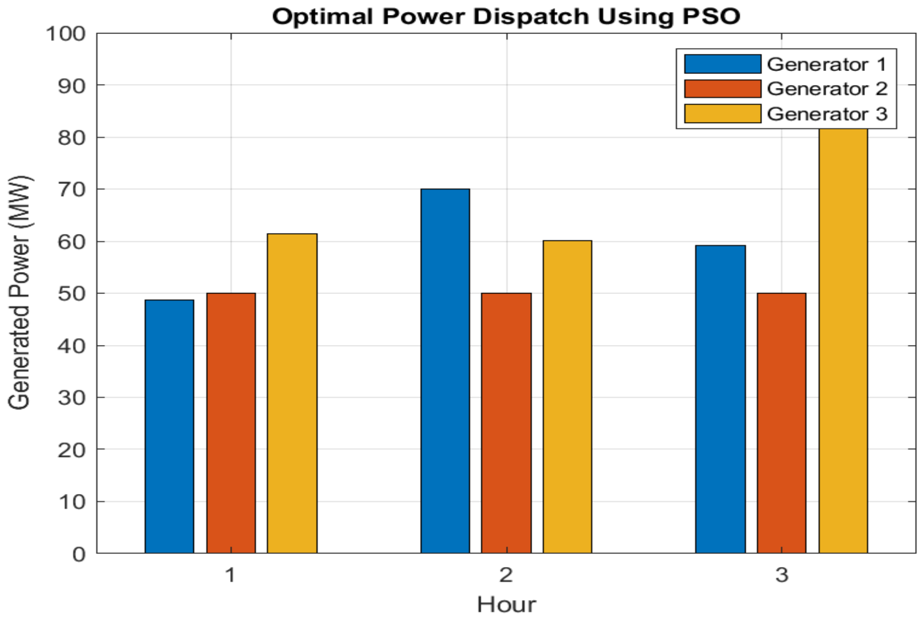

Figure 2 Optimal power Dispatch Using POS

Conclusion

This paper presented the application of the Particle Swarm Optimization (PSO) algorithm to solve the Optimal Economic Load Dispatch (OELD) problem of the Western Libyan Power System. The ELD problem was formulated as a constrained nonlinear optimization problem aiming to minimize the total fuel cost while satisfying power balance and generator operating limits. Practical generator data obtained from the Libyan power system were incorporated to ensure realistic modeling conditions. Simulation results under three different load levels (160 MW, 180 MW, and 200 MW) demonstrated that the PSO algorithm effectively determined the optimal power generation schedule for each unit while maintaining all operational constraints. The convergence curves showed rapid reduction in fuel cost during early iterations followed by stable convergence toward the optimal solution, confirming the fast convergence capability and robustness of the algorithm. The obtained results indicate that PSO provides an efficient and reliable solution for economic dispatch problems in real power systems.

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