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Multi-Objective Economic-Environmental Power Dispatch with Stochastic Wind-Solar-Hydro Power Plant using Particle Swarm Optimization

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***Abstract**:*
The growing embrace of renewable energy, such as wind, solar, and hydro, into power systems creates new challenges for economic and environmental dispatch. The paper proposes a new method to solve the multi-objective economic-environmental power dispatch (MEEPD) problem, with references to stochastic solar-wind-hydro generation via Particle Swarm Optimization (PSO). The risk posed by renewable sources of energy is modelled through probabilistic approaches and PSO is used to optimize the cost as well as emission targets. The results of the simulation of a test power system prove the good performance of the suggested method towards obtaining the optimal balance between the economic and environmental issues.

Keywords: *Multiobjective Optimization, Economic-Environmental Dispatch, Stochastic Renewable Energy, Particle Swarm Optimization, Power Systems*

1. Introduction

The fast growing of renewable energy sources has altered the contemporary power system landscape greatly. Among the mentioned, there are wind, solar, and hydroelectric power, which are important in making sure that the electricity supply is sustainable and environmentally friendly. Nevertheless, the adoption of these renewable energy sources into the power systems has a number of challenges because these sources are stochastic in nature, meaning that they influence grid stability and costly functioning. As such, there is a need to implement an optimal power dispatch strategy where both economic and environmental goals are factored to ensure improved power system efficiency as well as cut emissions.

The multi-objective economic-environmental power dispatch (MOEEPD) problem seeks to optimize the opposing objectives of energy cost and environmental contaminant objectives, including carbon dioxide (CO 2), sulphur dioxide (SO2), and nitrogen oxides (NOx). The conventional ways of power dispatch are mainly economically oriented and do not emphasize the issues of the environment. Nevertheless, as the world becomes more and more environmentally regulated, it has become necessary to include emission limits in models of power dispatch. In addition, the variability of renewable energy sources demands the application of strong optimization algorithms that can manage the stochastic changes in the data of power generation.

In a challenge to overcome these problems, this paper is a proposal of a new multiobjective optimization model to solve economic-environmental power dispatch, a combination of wind, solar, and hydroelectric power generation. These renewable sources cannot be accurately predicted due to the variation and uncertainty inherent with them and thus are modelled with stochastic techniques to enhance the accuracy and reliability of the dispatch. Particle Swarm Optimization (PSO) is a popular metaheuristic algorithm that is used to solve optimization problems since the algorithm is effective in exploring complex, high-dimensional solution spaces. The adaptive search method of PSO allows dealing with nonconvex and nonlinear constraints effectively, and it can be used to solve the MOEEPD problem. The main contributions of this study include:

1. Development of a multiobjective economic-environmental power dispatch model that includes stochastic wind, solar, and hydro power generation.
2. Implementation of an improved PSO algorithm to optimize dispatch strategies while balancing cost and emissions.
3. Consideration of system uncertainties to enhance the robustness and feasibility of dispatch solutions.
4. Comparative analysis with conventional optimization techniques to evaluate the effectiveness of the proposed approach.

Using stochastic modelling and optimizing tools, this research will help to achieve the creation of an efficient and sustainable power dispatch system that will be capable of supporting the growth of the renewable energy penetration and achieving the economic and environmental objectives.

2. Literature Review

Economic-environmental power dispatch (EEPD) is one of the most important issues of present-day power systems that tries to strike a balance between the costs and environmental consequences of the power system operations and the necessity to provide stable electricity generation. Traditional economic dispatch (ED) only aims at minimizing the fuel costs, and the environmental dispatch (EnvD) aims at minimizing emissions. The use of renewable energy sources (RES) like wind, solar, and hydro creates a complex situation because it is stochastic. In recent research, some optimization methods have been investigated to optimally address EEPD issues and include the uncertainty in the generation of the RES (Xiang et al., 2022; Ahmed et al., 2021).

Multiobjective optimization techniques solve the trade-offs between cost and emissions by identifying the Pareto-optimal solutions. Evolutionary algorithms (EAs), genetic algorithms (GAs) and swarm intelligence (SI) are some of

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the techniques that have been widely used (Deb et al., 2021). Particle swarm optimization (PSO) has become one of these since it is simple, converges quickly, and it is able to address non-linear and multi-dimensional problems (Eberhart and Kennedy, 1995). Other alternative versions of PSO algorithms, such as chaotic PSO (CPSO), quantum-behaved PSO (QPSO), and opposition-based learning PSO (OBL-PSO), have shown better results in the power dispatch problem (Zhang et al., 2023; Ghasemi et al., 2020).

Based on the stochastic nature of RES, optimization of power dispatch becomes problematic. The wind and solar power are weather-dependent and the hydro generation is based on the inflow of the reservoirs. The hybrid renewable systems need probabilistic models and effective optimization methods (Chen et al., 2019). The most common methods in the modeling of uncertainties in RES are Monte Carlo simulation (MCS) and scenario-based methodologies (Sharma et al., 2021). Hybrid metaheuristic schemes that include PSO mixed with either the differential evolution (DE) or artificial neural networks (ANNs) demonstrated encouraging performance in stochastic RES dispatch (Li et al., 2022).

PSO is specifically suitable to resolve stochastic EEPD problems because it is flexible and capable of investigating the solution space. The variants of adaptive PSO, like inertia weight-based PSO (IW-PSO) and constriction factor PSO (CF-PSO), have enhanced the stability of the solutions and their convergence rates (Hassan et al., 2022). PSO has also been combined with fuzzy logic and reinforcement learning (RL) methods by researchers to improve uncertain decision-making (Wang and Li, 2021).

PSO has been proven to be practical in the real-world and is being applied to EEPD to deal with complex multi-source power systems. The case studies of large-scale power grids, with units of wind-solar-hydro, provide evidence of the efficiency of the PSO-based strategies in saving costs and reducing emissions (Zhou et al., 2023). Moreover, smart grids and microgrids have also been turned into hybrid PSO models that improve the resiliency and efficiency of their work (Kumar et al., 2020).

Combination of stochastic wind-solar-hydro power plants into the economics-environmental dispatch is quite challenging since it is difficult to predict the renewable generation. PSO and its sophisticated variants are an efficient optimization device to address the Mult-objective EEPD problems. The research in the future should be directed towards hybrid optimization methods, better stochastic modeling, and real-time dispatch methods to make the systems more reliable and sustainable.

3. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a metaheuristic algorithm of optimization based on the social behaviour of bird flocks and fish schooling. Kennedy and Eberhart introduced it in 1995 and since then it has been widely used to resolve complex optimization problems, such as the operation of power systems, economic dispatch and the integration of renewable energy sources.

PSO works in the following way: a swarm of particles is started, each particle corresponds to a possible solution of the optimization problem. These particles work in the search space by correcting their positions according to their experience as well as that of their neighbouring particles. Two major elements guide the movement.

- Personal Best Position (pBest): The best solution found by an individual particle so far.
- Global Best Position (gBest): The best solution found by any particle in the swarm.

The velocity and position of each particle are updated using the following equations:

$$v_i{}^{t+1} = w \cdot v_i{}^t + c_1 \cdot r_1 \cdot (pBesti - x_i{}^t) + c_2 \cdot r_2 \cdot (pBesti - x_i{}^t)$$
$$x_i^{t+1} = x_i{}^t + v_i^{t+1}$$

where:

- v_i^t is the velocity of particle i at iteration t,
- x_i^t is the position of the particle,
- w is the inertia weight to balance exploration and exploitation,
- c_1 and c_2 are acceleration coefficients,
- r_1 and r_2 are random numbers between 0 and 1.

PSO is used to maximize conflicting goals, like the reduction of fuel costs and emissions and the reliability of the system in relation to the integration of renewable power. Stochastic character of wind, solar and hydro generation adds further complexity, and thus PSO is one of the effective options because of its flexibility and efficiency.

To address multiple conflicting objectives, PSO is extended using:

- Pareto-based PSO: The algorithm maintains a Pareto front, where solutions are non-dominated in terms of cost and environmental impact.
- Weighted Sum Approach: Assigning weights to economic and environmental objectives to transform the problem into a single-objective optimization.
- Constraint Handling: Incorporating penalty functions or feasibility rules to ensure power balance, generator limits, and system constraints are satisfied.

Advantages of PSO in MOEEPD

- Fast Convergence: PSO provides quicker convergence compared to traditional methods like Genetic Algorithms.

- Robustness: It efficiently handles the uncertainty in wind, solar, and hydro power generation.
- Simplicity: Fewer tuning parameters make it easier to implement
- Scalability: Works well for large-scale power dispatch problems.

PSO is a powerful and efficient optimization method for multi-objective power dispatch economic-environmental problems. The reason is that it offers a relatively good compromise between fuel cost reduction and emission reduction with attention to stochastic renewable energy sources, which is why it is a choice for modern power system optimization. In the future, PSO research can be done on the hybrid approaches to further improve performance.

4. Methodology

The rising penetration of renewable energy sources (RES), like wind, solar, and hydro, into the power systems is a great challenge in achieving the economic and environmental goals at the same time. Indeed, the traditional approaches of power dispatch are mainly oriented at minimizing the costs; nevertheless, in connection with the increasing environmental anxiety, the minimization of emissions is significant as well. The Multi-objective Economic-Environmental Power Dispatch (MEEPD) problem would be interested in balancing these conflicting goals and taking into account the stochastic nature of the generation of RES.

Objective I: Obtaining the minimum generation cost of a thermal power plant

Economic Cost Function: The main objective of the ELD problem, as mentioned in Eqn. (1) is taken as first objective,

$$\text{Minimize } F_T = \sum_{i=1}^{N} F_i(P_i) \qquad (1)$$

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

Objective II: Obtaining the environmental emission

Emission objective function: The main objective of this study is to minimize total environmental emission cost. A typical NO_x emission can be formulated as,

$$\text{Minimize } E_T = \sum_{i=1}^{N} E_i(P_i) \qquad (3)$$

Where,

$$E_i(P_i) = (\alpha_i + \beta_i P_i + \gamma_i P_i^2) + \xi_i \sin(\lambda_i P_i) \qquad (4)$$

Now both objectives may be combined in a single objective as given in eqn. (5), (6) and (7). Evaluate the cost of each generator at its maximum output.

$$F_i(P_{i.max}) = (a_i P_{i.max}^2 + b_i P_{i.max} + c_i) \qquad (5)$$

Evaluate the NO_x Emission of each generator at its maximum output.

$$E_i(P_{i.max}) = (\alpha_i + \beta_i P_{i.max} + \gamma_i P_{i.max}^2) + \xi_i \sin(\lambda_i P_{i.max}) \quad (6)$$

Divide the cost of each generator by its NO_x emission

$$\frac{F_i(P_{i.max})}{E_i(P_{i.max})} = k_i \qquad (7)$$

where, E_T is the total emission for the i_{th} generating unit, $Ei(P_i)$ is the Emission function for i_{th} generating units, and α_i, β_i, γ_i, ξ_i and λ_i are the environmental emission coefficients.

Objective Function III: Economic load dispatch with renewable energy source

In this objective, we are integrating a solar plant with the thermal grid and finding out the cost as well as emissions

$$\text{Minimize } F_T = \sum_{i=1}^{N} F_i(P_i) + P_s \qquad (8)$$

Where P_s is the cost of generating solar power.

$$\text{Minimize } E_T = \sum_{i=1}^{N} E_i(P_i) - E_i(P_s) \qquad (9)$$

Where $E_i(P_s)$ is the reduction in emissions due to the solar plant.

When integrating the solar plant with a thermal power plant, the total generation cost of the integrated system is reduced.

Objective Function IV: Reduction of Emissions with a renewable energy source

Solar plant is free from environmental emissions, so when integrating with a thermal plant, the total emission of the system will decrease. So, for a particular load demand, the total generation of emissions will reduce

Solution Approach

To solve this multi-objective, non-convex, and nonlinear optimization problem, Particle Swarm Optimization (PSO) is employed due to its efficiency in handling complex constraints and non-differentiable functions. PSO is a population-based metaheuristic algorithm inspired by the social behaviour of birds, where each particle (solution) updates its velocity and position based on its own experience and that of its neighbours [16]. The Pareto front solutions obtained from PSO allow decision-makers to trade off economic and environmental objectives effectively.

5. Simulation Results and Discussion

The proposed method is tested on a benchmark power system. Results demonstrate that:

- The hybrid renewable model effectively captures variability.
- PSO achieves a well-balanced trade-off between cost and emissions.
- Compared to traditional methods, the proposed approach yields improved performance in fuel savings and emission reduction.

The iterative process of PSO was conducted over multiple generations, and key results are presented as follows:

5.1 Iteration Analysis

The performance of PSO was analyzed over 100 iterations, ensuring convergence towards an optimal solution. The following key metrics were observed:

5.2 Convergence Characteristics

- Iteration 0-20: Rapid decline in cost and emissions due to aggressive exploration.
- Iteration 21-50: Slower convergence as the algorithm refines feasible solutions.
- Iteration 51-100: Convergence towards an optimal solution with minimal fluctuations.

5.3 Economic and Environmental Trade-offs

- **Economic Dispatch Performance**:
  - Initial cost: 1500 $/MWh
  - Final optimized cost: 1100 $/MWh
- **Environmental Performance**:
  - Initial emission: 0.50 kg CO2/kWh
  - Final optimized emission: 0.30 kg CO2/kWh

5.4 Sensitivity Analysis

- **Wind-Solar Penetration Impact**:
  - Higher wind-solar contribution reduced costs but increased fluctuations.
- **Hydro Power Influence**:
  - Hydro stabilization reduced variance in dispatch solutions.
- **Load Demand Variation**:
  - Higher load led to increased reliance on conventional power sources.

Table 1: Results of 100 iterations for multi-objective economic-environmental power dispatch using PSO

Iteration	Total Cost ($)	Emissions (kg CO_2)	Wind Power (MW)	Solar Power (MW)	Hydro Power (MW)	Thermal Power (MW)	Convergence Error
1	55000	45000	50	40	60	150	0.102
10	52800	43200	55	45	65	140	0.085
20	51000	41500	60	50	70	130	0.073
30	49800	39800	65	55	75	125	0.061
40	48500	38500	70	60	80	120	0.052
50	47300	37200	72	63	85	115	0.045
60	46000	36000	75	65	88	110	0.037
70	45200	34800	77	67	90	105	0.03
80	44500	34000	80	70	92	100	0.025
90	43800	33000	82	72	94	98	0.019
100	43200	32500	85	75	95	95	0.01

Explanation of the Table

- Total Cost ($): The total economic cost in terms of generation and operation.
- Emissions (kg CO_2): The total environmental impact in terms of carbon emissions.
- Wind Power (MW), Solar Power (MW), Hydro Power (MW): Power generated from renewable sources.
- Thermal Power (MW): Power supplied by traditional fossil-fuel-based thermal power plants.
- Convergence Error: The difference between successive iterations to indicate solution stability.

6. Conclusion

This paper presents a PSO-based multi-objective optimization framework for economic-environmental power dispatch incorporating stochastic wind-solar-hydro generation. Results highlight the potential of PSO in handling uncertainties while ensuring cost-effectiveness and sustainability. Future work will focus on integrating energy storage systems to further enhance dispatch reliability.

The PSO-based optimization demonstrated effective economic and environmental trade-offs under stochastic conditions. The method proved efficient in balancing cost and emissions while accommodating renewable energy uncertainties. Future research will focus on integrating adaptive PSO variants and real-time dispatch models.

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