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Research paper

Multi-objective optimal power flow in the presence of intermittent renewable energy sources

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Abstract

This paper solves a multi-objective optimal power flow (MO-OPF) problem in a wind-thermal power system. Here, the power output from the wind energy generator (WEG) is considered as the schedulable, therefore the wind power penetration limits can be determined by the system operator. The stochastic behavior of wind power and wind speed is modeled using the Weibull probability density function. In this paper, three objective functions i.e., total generation cost, transmission losses and voltage stability enhancement index are selected. The total generation cost minimization function includes the cost of power produced by the thermal and WEGs, costs due to over-estimation and the under-estimation of available wind power. Here, the MO-OPF problems are solved using the multi-objective glow-worm swarm optimiza-tion (MO-GSO) algorithm. The proposed optimization problem is solved on a modified IEEE 30 bus system with two wind farms located at two different buses in the system.

Keywords: *Optimal Power Flow; Renewable Energy Sources; Multi-Objective Optimization; Uncertainty; Voltage Stability.*

1. Introduction

The electrical power grid is undergoing a transformation from a number of different perspectives. There is an increasing interest around the world in integrating higher levels of variable renewable energy resources (RERs) such as wind and solar photovoltaic (PV) into electric power systems. The power output from RERs is often uncertain, intermittent and uncontrollable. The ultra-high levels of RERs have a major impact on planning and operation of electric power grids [1]. Optimal Power Flow (OPF) is a highly constrained and non-linear optimization problem. The aim of OPF problem is to optimize an objective function, and keep the power outputs of generating units, shunt capacitors, bus voltages and transformer tap settings within their secure limits. The classical OPF techniques include Gradient method, Quadratic programming method, Interior point method, Newton method and linear programming method. To overcome inherent disadvantages of classical optimization methods, meta-heuristic optimization techniques have been developed [2].

A multi-objective OPF MO-OPF model of multiple-energy system, helping to achieve more comprehensive and efficient use of energy and multiple-energy input to reduce costs is proposed in [3]. An OPF problem to optimize the emission release due to nitrogen oxides, carbon oxides and sulfur oxides with system operating cost as constraint for power system with WEGs is proposed in [4]. Reference [5] presents a model for the optimal scheduling of hydrothermal power systems with multiple hydro reservoirs. In [6], a Gray coded genetic algorithm is proposed for the economic dispatch (ED) problem of wind-thermal power system, and to determine the optimal power dispatch method for the proper utilization of wind power. A multi-objective optimized scheduling for power system composed of thermal, hydro and wind power is proposed in [7] considering the system operation cost, pollutant emission of thermal power and the net loss of power system as the multiple objectives. An approach for solving the ED problem in the presence of RERs is presented in [8]. An informative differential evolution (DE) with self adaptive re-clustering algorithm for solving an optimal energy and spinning reserve scheduling problem of a power system with WEGs is proposed in [9].

To the best of the author' knowledge, the MO-OPF considering wind power forecast uncertainties have not been considered so far. The present paper aims at bridging this gap. In this paper, the MO-OPF is performed by considering 3 conflicting objectives, i.e., total generation cost, transmission losses and voltage stability enhancement index, in the presence of wind forecast uncertainty. Here, the OPF problem is formulated by considering the factors involved due to the uncertainty of wind power. The OPF solution indicate the minimum real power requirement based on the wind variability at a particular location and reactive power capacity to be installed in the wind farm to maintain a satisfactory level of system voltage profile. This paper has a significant role in determining trade-off solution between three objective functions.

The rest of this paper is organized as follows: Section 2 presents the proposed problem formulation. The description of multi-objective glowworm swarm optimization (MO-GSO) algorithm is presented in Section 3. The simulation results and discussion is presented in Section 4. Finally, the contributions with concluding remarks are presented in Section 5.

2. Proposed problem formulation

2.1. Objective 1: generation cost minimization

Here, the objective function is formulated as minimization of both operating cost of thermal and WEGs along with factor involved for over/under estimation of wind power [10] and it is expressed as,

Minimize,

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$$J_1 = \sum_i^{N_g} C_i(P_{gi}) + \sum_j^{N_w}[C_{wj}(P_{wj}) + C_{p,wj}(P_{wj,avg} - P_{wj}) + C_{r,wj}(P_{wj} - P_{wj,avg})] \quad (1)$$

First term in Eq. (1) is the generation cost of thermal generators, and it is given by,

$$C_{Gi}(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (2)$$

Second term in Eq. (1) is operating cost for the power drawn from the WEG,

$$C_{wj}(P_{wj}) = d_j P_{wj} \quad (3)$$

Third term in Eq. (1) is cost obtained from the concept of under-estimation of wind power and it is termed as the penalty cost. This cost is expressed as [11],

$$C_{p,wj}(P_{wj,avg} - P_{wj}) = K_{p,j} \int_{P_{wj}}^{P_{r,j}} (p - P_{wj}) f_p(p) dp \quad (4)$$

Fourth term in Eq. (1) is cost due to available wind power being less than the scheduled one. This cost is termed as over-estimation cost, and it is expressed as,

$$C_{r,wj}(P_{wj} - P_{wj,avg}) = K_{r,j} \int_0^{P_{wj}} (P_{wj} - p) f_p(p) dp \quad (5)$$

2.2. Objective 2: transmission losses minimization

For the reactive power optimization problem, the transmission losses minimization is considered as an objective function. This objective function is expressed as [12],
Minimize,

$$J_2 = \frac{1}{2} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} G_{ij}[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad (6)$$

2.3. Objective 3: voltage stability enhancement index (VSEI) minimization

In this paper, to monitor the voltage stability, the L-index of the demand buses is considered. L-index uses the information from the power flow solution, and is in the range of 0 (i.e., no load) to 1 (i.e., voltages collapse). The VSEI is formulated as,
Minimize,

$$J_3 = \text{VSEI} = \sum_{j=N_G+1}^{N} L_j^2 \quad (7)$$

2.4. Problem constraints

2.4.1. Equality constraints

These are the typical power flow equations, and they are expressed as,

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) = 0 \quad (8)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) = 0 \quad (9)$$

2.4.2. Inequality constraints

Generator Constraints:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \; i = 1,2,3,\dots,N_G \quad (10)$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \; i = 1,2,3,\dots,N_G \quad (11)$$

$$P_{Wj}^{min} \leq P_{Wj} \leq P_{Wj}^{max} \; i = 1,2,3,\dots,N_W \quad (12)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \; i = 1,2,3,\dots,N_G \quad (13)$$

Transformer Tap Constraints:

$$T_i^{min} \leq T_i \leq T_i^{max} \; i = 1,2,3,\dots,N_T \quad (14)$$

Switchable VAR sources:

$$Q_{Ci}^{min} \leq Q_{Ci} \leq Q_{Ci}^{max} \; i = 1,2,3,\dots,N_C \quad (15)$$

Security constraints:

$$S_{Li} \leq S_{Li}^{max} \; i = 1,2,3,\dots,N_{line} \quad (16)$$

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max} \; i = 1,2,3,\dots,N_L \quad (17)$$

The uncertainty modeling of WEGs is presented in [13].

3. Multi-objective glowworm swarm optimization (MO-GSO)

GSO algorithm [14] is a new swarm based optimization technique derived from the natural glowworm's activities in the night. Glowworms exercise in group, their inter-attraction and interaction with each other by one's luciferin. If a glowworm emits luciferin more light, it can attract more glowworms move toward it. To simulate this natural phenomena, combined with characteristics of natural glowworm populations, each glowworm at the owns field of view in search for the glowworm which release the strongest luciferin, also move to the strongest glowworm [15]. GSO starts by placing glowworms randomly in workspace, so that they are well dispersed. Every generation has luciferin-update phase, movement-phase based on a transition principle. The flow chart of MO-GSO for solving MO-OPF problem is depicted in Figure 1.

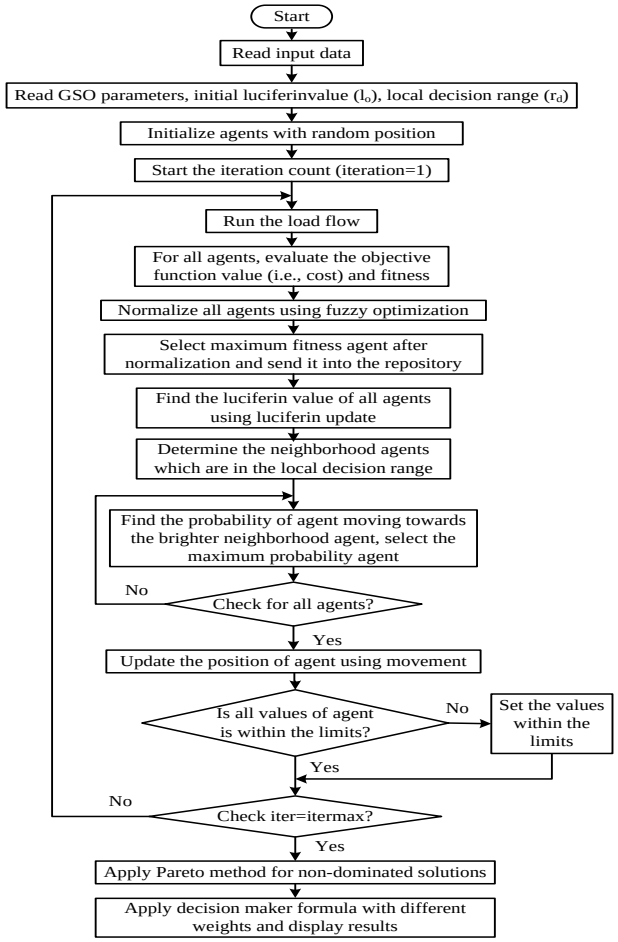


Fig. 1: Flowchart of MO-GSO Algorithm for Solving the MO-OPF Problem.

4. Results and discussion

The proposed MO-GSO algorithm for solving MO-OPF problem is demonstrated on modified IEEE 30 bus, 41 branch test system [16]. IEEE 30 bus system consists of 6 generating units, of which 4 are considered to be thermal generating units located at buses 1, 2, 5 and 8; and 2 are assumed to be WEGs, located at buses 11 and 13. Here, a total of 24 control variables are considered, and they are 3 thermal generating units active power outputs, 2 WEGs active power outputs, 6 generator bus voltage magnitudes, 4 transformer tap settings and 9 bus shunt susceptances. The following 3 case studies are performed in this paper:

4.1. Case 1: generation cost and transmission losses minimization

In this case, total generation cost and transmission losses are optimized simultaneously using MO-GSO algorithm. Figure 2 depicts the Pareto optimal front for total generation cost and transmission losses minimization using MO-GSO algorithm. Table 1 presents the best compromised solution obtained for Case 1. This solution has generation cost of 1012.30$/hr, and losses of 7.9871MW.

4.2. Case 2: generation cost and VSEI minimization

In this Case, the generation cost and VSEI objectives are optimized simultaneously using MO-GSO algorithm. Figure 3 depicts the Pareto optimal front for total generation cost and VSEI minimization objective functions. Table 1 also shows the objective function values for Case 2. The best compromise solution obtained has total generation cost of 998.62$/hr and VSEI of 0.1634.

4.3. Case 3: generation cost, transmission losses and vsei minimization

In this Case, all 3 objective functions are optimized simultaneously. Table 1 shows the optimum objective function values for Case 3. Figure 4 depicts the Pareto optimal front for Case 3. The best compromise solution obtained has generation cost of 1034.02$/hr, transmission losses of 8.3252MW and VSEI of 0.1737.

Table 3: Optimum Solutions for Cases 1, 2 and 3 Using MO-GSO

Objective Function Values	Case 1	Case 2	Case 3
Generation Cost (in $/hr)	1012.30	998.62	1034.02
System Losses (in MW)	7.9871	11.3101	8.3252
VSEI	0.1845	0.1634	0.1737

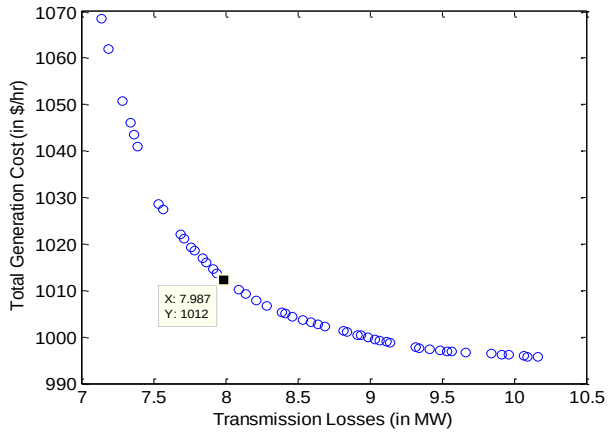


Fig. 2: Pareto Optimal Front of Total Cost and Transmission Losses for Case 1.

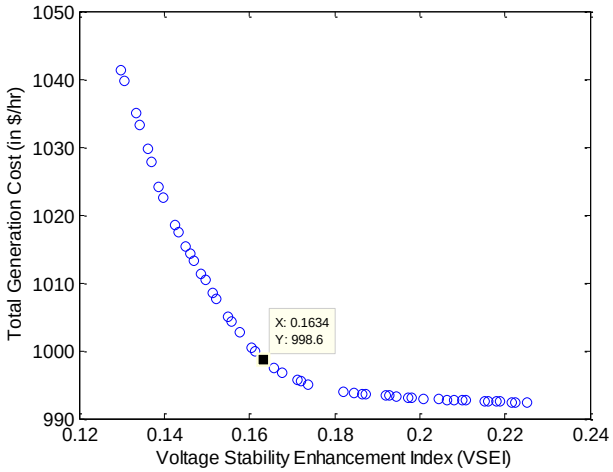


Fig. 3: Pareto Optimal Front of Total Cost and VSEI for Case 2.

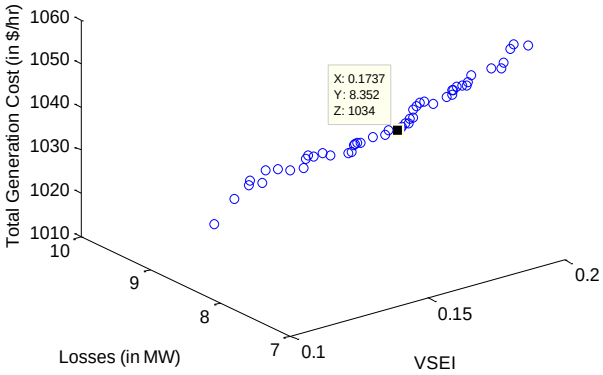


Fig. 4: Pareto Optimal Front of Total Cost, Losses and VSEI for Case 3.

5. Conclusions

This paper solves the multi-objective optimal power flow (MO-OPF) problem in a wind-thermal power system using the multi-objective glowworm swarm optimization (MO-GSO) algorithm. An approach is proposed in this paper to include WEGs in an OPF problem. The stochastic nature of wind speed and power is represented by Weibull PDF. In addition to the classical cost minimization, the factors to account for under and over estimation of available wind power are selected in this paper. It exhibits the OPF formulation with factors involved in the intermittency of wind power and MO-GSO algorithm is adopted to solve the problem. The simulation results for MO-OPF problems are presented on modified IEEE 30 bus system. These results show the suitability and effectiveness of MO-GSO algorithm for solving MO-OPF problem.

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