



Physical-inspired Method for Optimal Control and Power Flow Optimization of Electrical Grid Enriched with Renewable Energy Sources

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ABSTRACT

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Due to the need for better reliability, clean environment, reduced losses, and lower costs, renewable energy sources (RES) like wind and solar have seen increased integration into power systems in recent years. This study applies the Gravitational Search Algorithm (GSA), a physics-inspired optimization method, to address optimal control, optimal power flow (OPF), and environmental index optimization (EIO) in grids incorporating RES. The algorithm was tested on a standard power grid with both wind turbines and photovoltaic units. In terms of computational effort, convergence speed, and solutions performance, the simulation results conclusively confirm the efficiency and reliability of the proposed method for solving OPF and EIO.

1. INTRODUCTION

Increasing electricity demand is largely driven by population growth, digital expansion, and industrialization. This has led to a notable rise in research and implementation of renewable energy technologies in recent years [1]-[2]. Among these, wind turbines stand out due to their potential for significant energy contribution. However, wind energy is highly variable, as wind speed fluctuations can adversely affect power quality, particularly voltage and current stability in the grid [3].

Optimal Power Flow (OPF) remains a vital analytical tool for power system operations. It plays a crucial role in the planning, control, and energy management of electrical networks [4]. The concept of OPF has evolved over more than six decades, beginning with Carpenter's early discussion in 1962 [5] and further developed into a formal model by Dommel and Tinney in 1968 [6].

Electric power plants using conventional fossil fuels are major contributors to air pollution, primarily due to the combustion of coal, oil, and gas [7]. Coal, in particular, releases significant amounts of carbon dioxide (CO₂) along with harmful gases like sulfur oxides (SO_x) and nitrogen oxides (NO_x). The type and amount of emissions depend on the fuel's composition and quality [7]-[8]. The environmental or emission index is a key measure used to assess environmental impact [3]. Numerous approaches have been proposed to mitigate these emissions.

Following the 1990 amendment to the U.S. Clean Air Act

and rising public concern over environmental issues, power producers were required to adopt cleaner technologies and implement strategies to reduce emissions from electricity generation [8].

The integration of RES, such as photovoltaic (PV) systems and wind turbines (WTs), varies based on geographic and climate conditions. However, their output is inherently variable and difficult to predict [9].

2. PROBLEM FORMULATION

Generally, the OPF problem expressed as follows [10].

$$\text{Min } f(x, u) \quad (1)$$

Subject to

$$h(x, u) = 0 \quad (2)$$

$$g(x, u) \leq 0 \quad (3)$$

$f(x, u)$ is the goal, with $h(x, u)$ and $g(x, u)$ as the system equality and inequality bounds; x and u define its state and control variables.

2.1 Objective functions

2.1.1 Cost optimization

The quadratic objective function of cost optimization cost in (\$/h) for all generators as given below [10]-[13]

$$f(x, u) = \min \sum_{i=1}^{n_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \quad (4)$$

P_{gi} and n_g are the generated active power and the number of generators. a_i , b_i and c_i are the generator cost coefficients.

2.1.2 Environmental index optimization

Generally, the EIO problem can be expressed as follows

$$\min f(x, u) = \min \sum_{k=1}^{n_k} 10^{-2} (\alpha_{ik} + \beta_i P_{gi} + \gamma_i P_{gi}^2) + \zeta_i \exp(\lambda_i P_{gi}) \quad (5)$$

$\alpha_i, \beta_i, \gamma_i, \zeta_i$ and λ_i are the coefficients of emission.

2.1.3 Voltage deviation (VD) optimization

$$\min F(x, u) = \min VD(x, u) = \min \sum_{i=1}^{n_L} |V_i - V_i^{ref}| \quad (6)$$

Hence, x and u can be expressed as given

$$x^t = \{P_{g1}, |V_{L1}|, \dots, |V_{L_{nL}}|, Q_{g1}, \dots, Q_{g_{n_g}}, S_1, \dots, S_{n_{br}}\} \quad (7)$$

Here, P_g , Q_g , V_L and S_i are the slack bus active power, reactive power generation, load buses amplitude voltage, and branch apparent power flows. n_g , n_L and n_{br} are the total numbers of generators, load buses, and branches [11].

$$u^t = \{P_{g2}, \dots, P_{g_{n_g}}, |V_{g1}|, \dots, |V_{g_{n_g}}|, Q_{1_{com}}, \dots, Q_{n_{com}}, T_1, \dots, T_{n_T}\} \quad (8)$$

Here, P_g , V_g and Q_{com} denotes, respectively, active power of generators except slack bus, generators magnitude voltages, and the reactive power of compensators. T , n_{com} and n_T represents transformer tap settings, total numbers of compensators and transformers, respectively [10]-[15].

2.1.5 Equality constraints

These constants is represented by power flow equations

$$\begin{cases} P_{gi} = P_i + P_{Li} \\ Q_{gi} - Q_{comk} = Q_i + Q_{Li} \end{cases} \quad (9)$$

P_i, Q_i, P_{Li}, Q_{Li} and Q_{comi} are, respectively, the bus active and reactive power, the PQ bus power, and power compensation at bus i .

2.1.6 Inequality constraints

The inequality constraints are presented by limits of variables as [16]-[18].

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} \quad \text{where } i = 1, \dots, n_g \quad (10)$$

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \quad \text{where } i = 1, \dots, n_g \quad (11)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \text{where } i = 1, \dots, n_b \quad (12)$$

$$\theta_i^{\min} \leq \theta_i \leq \theta_i^{\max} \quad \text{where } i = 1, \dots, n_b \quad (13)$$

$$T_i^{\min} \leq T_i \leq T_i^{\max} \quad \text{where } i = 1, \dots, n_T \quad (14)$$

$$Q_{comi}^{\min} \leq Q_{comi} \leq Q_{comi}^{\max} \quad \text{where } i = 1, \dots, n_{com} \quad (15)$$

$$S_{ij} \leq S_{ij}^{\max} \quad \text{where } i = j = 1, \dots, n_b \quad (16)$$

$S_{kj}^{\max}$ is the maximum apparent power flow.

2.2 Photovoltaic and wind turbines modelling

2.2.1 Photovoltaic

The PV power P_{PV} is calculated as follow [19]-[20]

$$P_{PV} = P_{STC} \frac{I_s}{1000} [1 + \gamma(T_c - 25)] \quad (17)$$

P_{STC} and γ are the PV maximum power and the temperature coefficient. I_s and T_c are the solar irradiation and ambient temperature of the site. T_c is calculated using the Nominal Operating Cell Temperature (NOCT) [21]

$$T_c = T_a + \frac{I_s}{800} (T_{NOCT} - 20) \quad (18)$$

T_a is the ambient temperature in ($^{\circ}\text{C}$), and T_{NOCT} is the module's NOCT in ($^{\circ}\text{C}$) [20]

2.2.2 Wind turbines

As per [19]-[21], the power curve can be represented by a function divided into 3 segments.

$$P_{WT} = \begin{cases} 0 & v \leq v_{ci} \quad \text{and} \quad v \geq v_{co} \\ \frac{v^2 - v_{ci}^2}{v_{nom}^2 - v_{ci}^2} P_{WT_nom} & v_{ci} < v < v_{nom} \\ P_{nom} & v_{nom} < v < v_{co} \end{cases} \quad (19)$$

Where, P_{WT_nom} , v_{nom} , v_{ci} and v_{co} are, respectively, the rated power, rated wind speed, switch-on wind speed and switch-off wind speed of the WT; P_{WT} is denote the output power of the WT and v is the wind speed [19].

3 GRAVITAIONAL SEARCH ALGORITHM

The Gravitational Search Algorithm (GSA) is one of the newest stochastic search algorithm introduced by Rashedi et al., [22] is a population-based metaheuristic inspired by Newtonian laws gravity [23]. Agents, modeled as masses, attract each other based on gravitational force, which depends on their mass and distance. Better-performing (heavier) agents move slower, guiding others toward optimal solutions [22]-[25].

In the GSA, each agent is characterized by four key elements: its position, inertial mass, active gravitational mass, and passive gravitational mass. The agent's position represents a candidate solution, while its masses are calculated through a fitness evaluation [24]. GSA can be

viewed as a self-contained system of interacting masses, functioning like a simplified artificial universe governed by Newton's laws of gravity and motion. In a system with N_a agents, the location of i^{th} agent is represented by

$$x_i = (x_i^1, \dots, x_i^d, \dots, x_i^D) \quad \text{where} \quad i = 1, \dots, N_a \quad (20)$$

In the d^{th} dimension, x_i^d is the position of i^{th} agent. Based on Newton's law of gravitation, mass j exerts a force on mass i at time t . This force randomly calculated as follows

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t)) \quad (21)$$

In this context, M_{pi} and M_{aj} refer to the masses of objects i and j , respectively. $G(t)$ is the constant of gravity and $R_{ij}(t)$ is the distance between agents i and j . The velocity and position of agent i are determined as [25]

$$v_i^d(t+1) = \text{rand}_i \times v_i^d(t) + a_i^d(t) \quad (22)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (23)$$

The gravitational constant G , initially set at random, gradually decreases over time to improve search precision.

$$G = G_0 \exp\left(-\alpha \frac{t}{t_{\max}}\right) \quad (24)$$

α as a user-defined parameter. Typically, $G_0=100$ and $\alpha=20$. According to Newton's principles, heavier agents exert stronger attraction but exhibit slower movement.

4 SIMULATION, RESULTS AND DISCUSION

The IEEE 30-bus system with 5 generators is used to evaluate the proposed algorithm. It includes 30 buses, 6 generators, and 41 branches. One bus is designated as the reference (slack) bus, buses with generators are PV buses, and the rest are PQ (load) buses. Capacitors compensation are available at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29. Network data's are detailed in [26]. The one-line diagram of test system is shown in Figure 1.

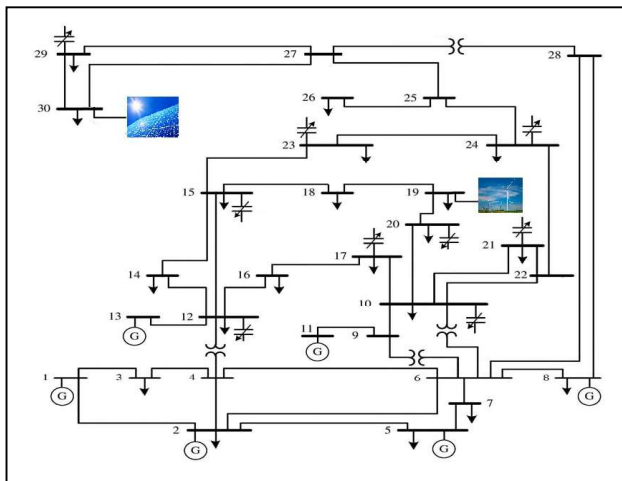


Figure. 1 Single-line diagram of test system

4.1. Case 1 : Cost optimization

The cost function (5), results in a 642.88 (\$/h), which is 19.815% lower than the initial case (without PV and WT). Figure 2 illustrates the convergence of cost function. Table 1 lists the optimal control variables.

4.2. Case 2 : Environmental index optimization

EIO reduction reached 0.219 (ton/h), that is 97.796% improvement. The optimal control variables for each objective function are provided in Table 1, with GSA's EIO convergence shown in Figure 3.

4.3 Case 3 : Voltage deviation optimization

The voltage deviation was reduced to 0.091 (pu), a 92.08% improvement over the initial case. The optimal control settings for this case is listed in Table 1, and the emission convergence is shown in Figure 4.

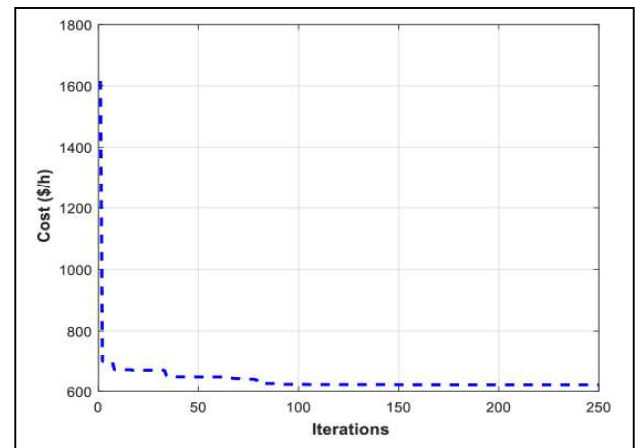


Figure. 2 Cost optimization for case 1

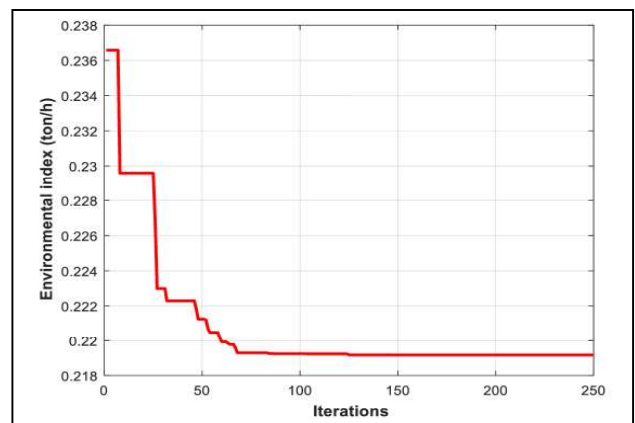


Figure. 3 Environmental index optimization for case 2

4.4 Case 4 : Multi-objective optimization

Multi-objective optimization, including cost, power loss, and voltage deviation, is also summarized in Table 1, with convergence characteristics displayed in Figure 5.

Since the output capacities of WT and PV vary due to being considered random variables influenced by

geographic and meteorological factors, they cannot be the control variables in the OPF problem. Therefore, the results obtained in Table 1 can be considered approximate predicted OPF results. Figure 6 shows the optimal magnitudes voltages obtained for all cases.

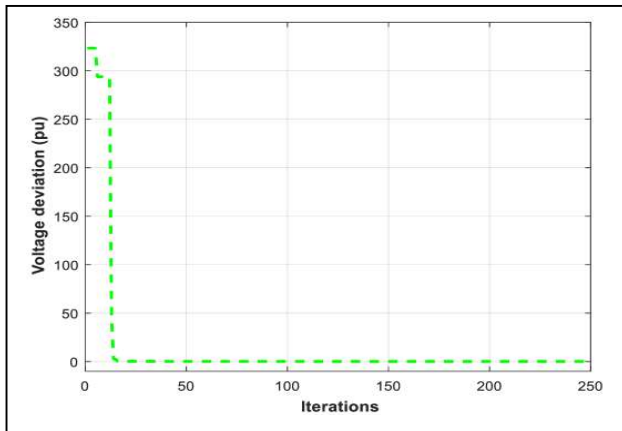


Figure. 4 Voltage deviation of case 3

Table 1. Controles variable setting

Control variables	Case 1	Case 2	Case 3	Case 4
PG ₂	41.662	66.366	53.099	43.795
PG ₅	17.826	40.634	41.596	28.261
PG ₈	12.154	13.611	24.034	28.482
PG ₁₁	10.002	29.999	19.505	19.745
PG ₁₃	32.159	33.665	30.581	14.007
VG ₁	1.061	1.039	1.004	1.022
VG ₂	1.041	1.030	1.002	1.012
VG ₅	0.999	1.001	0.996	0.999
VG ₈	1.012	0.971	1.008	0.998
VG ₁₁	1.040	1.060	1.045	1.055
VG ₁₃	1.003	0.985	1.016	1.025
V _{PV-19}	1.021	1.035	1.002	1.007
V _{WT-30}	1.006	1.049	0.997	1.015
Q ₁₀	1.630	0.827	2.027	3.429
Q ₁₂	2.136	4.705	2.157	1.326
Q ₁₅	4.136	4.212	1.814	2.267
Q ₁₇	3.661	3.932	1.976	3.215
Q ₂₀	3.671	2.122	2.051	0.793
Q ₂₁	3.249	2.482	4.675	2.966
Q ₂₃	2.576	3.270	4.997	4.813
Q ₂₄	2.521	3.573	4.973	4.984
Q ₂₉	1.770	0.539	2.195	1.760
T ₆₋₉	1.058	0.921	1.025	1.010
T ₆₋₁₀	0.934	0.971	0.903	0.969
T ₄₋₁₂	0.990	1.054	0.977	0.996
T ₂₈₋₂₇	1.024	0.937	0.943	0.979
Cost	620.78	0.22	648.24	643.261
Loss	7.277	4.001	3.518	4.613
Loss	25.671	4.660	13.989	18.026
EIO	-	0.219	-	-
VD	0.3117	0.326	0.091	0.128
Slack	145.21	10.72	100.11	100.773
P _{WT-19}	32.883	32.381	32.907	33.16
P _{PV-30}	19.781	19.780	19.779	19.78
CPU	31.59	31.97	27.71	31.24

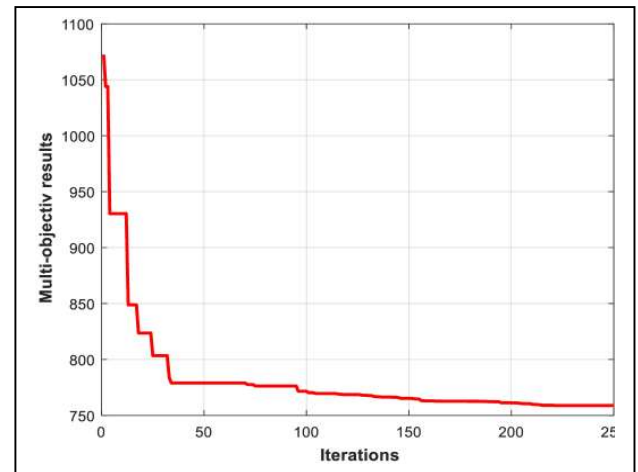


Figure. 5 Multi-objective results for case 4

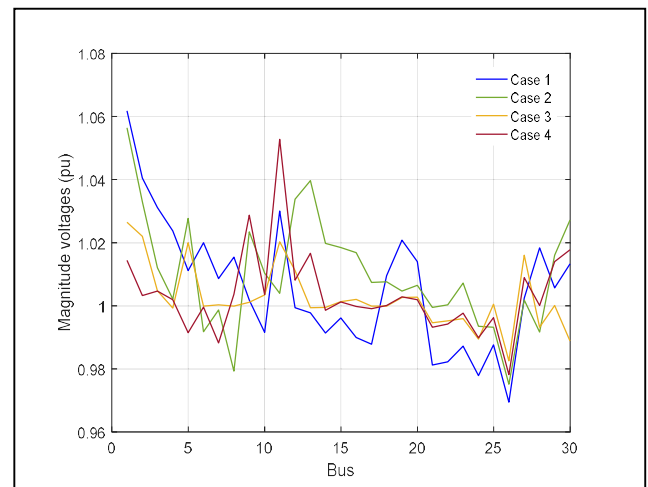


Figure. 6 Magnitude voltage for cases 1, 2, 3, and 4

Table 2. Comparison of obtained and literature results

Methods		Case 1	Case 2	Case 3
Methods	Ref			
MTFWO	[13]	800.47	0.366	0.906
FFA	[11]	-	-	0.2189
GWO	[16]	801.25	-	-
FFA-JAYA	[15]	800.48	0.365	0.904
GSA	[12]	-	0.2150	-
MSA	[17]	-	0.2048	-
ABC	[18]	800.66	0.3650	0.9209

4 CONCLUSIONS

This study successfully applies the GSA to address multi-objective optimal power flow. The GSA demonstrates high efficiency in solving multiple optimization problems, making it a powerful approach for addressing complex optimization tasks in engineering. The flexibility of GSA framework is further verified through systematic modifications of parameters such as N_a , α and G_0 . In terms of solution quality, the proposed approach outperforms other methods and its robustness is rigorously evaluated using best-, average-, and worst-case performance metrics. Simulation results conclusively confirm the method's efficiency and reliability, highlighting its adaptability to complex scenarios.

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