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Optimal Placement of SVC and OPF Solution Using Gravitational Search Algorithm Considering Ramp-Rate Constraints

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Abstract: In this paper we present a Gravitational Search Algorithm (GSA)-based OPF (Optimal Power Flow) problem based on Static Var Compensator (SVC) and generator ramp rate constraints. The OPF problem is designed to minimize generation fuel cost and voltage deviation while satisfying power balance equations and operating limits of generators, transformers, transmission lines and reactive power sources. An SVC is placed on the weakest bus under consideration to mitigate voltage deviation and is a controllable reactive power injection device. The proposed GSA can cope with the nonlinear and constrained nature of the OPF problem by adaptively interacting among possible solutions. We evaluate the effectiveness of the method on the IEEE 14-bus test system and compare it with Particle Swarm Optimization (PSO). The simulation results demonstrate that the proposed approach achieves lower generation cost, transmission losses, better voltage profile, and faster convergence than PSO. These results support the idea that integrated GSA, SVC compensation and ramp rate constraints are an effective and computationally efficient solution for practical application of OPF in power systems.

Keywords: Optimal Power Flow, Gravitational Search Algorithm, Static Var Compensator, Ramp-Rate Constraint, Voltage Deviation, Economic Load Dispatch, FACTS Devices

I. INTRODUCTION

Optimal Power Flow (OPF) is important for the economical, secure, and reliable operation of modern power systems. Increasing demand for electricity, increasing system complexity, integration of renewable energy, and operational constraints have made efficient power system optimization a research area of interest. OPF aims to determine the optimal operating condition that minimizes fuel cost, transmission losses, voltage deviation, or other performance measures while meeting power balance equations and system operating limits [1]–[11].

Due to the nonlinear, non-convex, and very constrained nature of OPF, conventional optimization techniques are unable to achieve high-quality global solutions. To combat this problem, evolutionary and metaheuristic approaches such as Genetic Algorithm (GA), Simulated Annealing (SA), Evolutionary Programming (EP), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and several hybrid optimization approaches have been successfully applied to OPF and Economic Dispatch (ED) problems [12]–[27]. Such algorithms can improve the search capabilities and robustness of the optimization problems for large-scale optimization problems.

The use of Flexible AC Transmission System (FACTS) devices has further improved OPF performance by supporting power transfer ability, voltage stability, reactive power management, and security. Several studies have studied the application of UPFC, GUPFC, and IPFC devices in economic dispatch, optimal power dispatch, reactive power optimization, and security enhancement problems [12], [13], [18], [19], [28]–[31]. Nevertheless, we have not focused on the issue of generator ramp-rate constraints, optimal placement of SVC, and Gravitational Search Algorithm (GSA)-based optimization.

In a practical power system, generator ramp-rate limits need to be implemented so that generation scheduling is feasible and operating conditions can be met. In addition, the placement of SVCs is also mandatory for voltage profile improvement and reactive power support. Therefore, this paper proposes a GSA-based OPF with an optimal placement of SVCs and generator ramp-rate constraints. The weakest bus is identified by voltage deviation analysis, and the best SVC is selected to manage voltage. The proposed GSA exploits the gravitational interactions between the candidate solutions to achieve effective global exploration and fast convergence.

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Our proposed method is tested on the IEEE 14-bus test and compared to the Particle Swarm Optimization (PSO) algorithm. The simulations reveal better fuel cost minimization, reduced transmission losses, better voltage profile, and low computational time.

The main contributions of this work are summarized as follows:

1. Development of an OPF model with generator ramp-rate constraints and SVC compensation.
2. Identification of the optimal SVC location based on voltage deviation analysis.
3. Gravitational Search Algorithm for solving the constrained OPF problem.
4. Comparison of GSA and PSO on the IEEE 14-bus system.
5. We show improved economic performance with lower power loss and voltage stability.

II. PROBLEM FORMULATION

The Optimal Power Flow (OPF) problem aims to determine the optimal settings of power system control variables while satisfying network operating constraints. In this work, the OPF problem is formulated to minimize generation fuel cost and voltage deviation by optimally adjusting generator outputs, generator voltages, transformer tap settings, reactive power sources, and SVC compensation.

A. Objective Functions

i. Fuel Cost Minimization

The economic objective of OPF is to minimize the total fuel cost of thermal generating units, which can be expressed as

$$F_1 = \sum_{i=1}^{N_G} C_i\,(P_{Gi})$$

where N_G is the number of generating units and $C_i(P_{Gi})$ represents the fuel cost function of generator i.

The fuel cost characteristic of each generating unit is represented by a quadratic function:

$$C_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2$$

where a_i, b_i, and c_i are the fuel cost coefficients of generator i.

ii. Voltage Deviation Minimization

To improve voltage profile and system security, the voltage deviation objective is formulated as

$$F_2 = \sum_{i=1}^{N_B} |V_i - V_{ref}|$$

where V_i is the voltage magnitude at bus i, V_{ref} is the reference voltage 1.0 p.u., and N_B is the total number of buses. A lower value of F_2 indicates a better voltage profile throughout the network.

B. Equality Constraints

The equality constraints represent the power flow balance equations that must be satisfied at every bus in the system.

Active Power Balance

$$P_{Gi} - P_{Di} - P_i(V,\delta) = 0$$

Reactive Power Balance

$$Q_{Gi} - Q_{Di} + Q_{SVC} - Q_i(V,\delta) = 0$$

Where, P_{Gi}, Q_{Gi} are generator active and reactive powers, P_{Di}, Q_{Di} are load demands, Q_{SVC} is the reactive power injected by the SVC, $P_i(V,\delta)$ and $Q_i(V,\delta)$ are bus power injections obtained from load flow equations.

C. Inequality Constraints

The operating limits of power system components are represented as inequality constraints.

Generator Active Power Limits $P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}$

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Generator Reactive Power Limits $Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}$

Generator Voltage Limits $V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max}$

Transformer Tap Limits $T_i^{min} \le T_i \le T_i^{max}$

Shunt Reactive Power Limits $Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}$

Load Bus Voltage Limits $V_i^{min} \le V_i \le V_i^{max}$

Transmission Line Flow Limits $S_{Li} \le S_{Li}^{max}$

where S_{Li} is the apparent power flow through transmission line i.

D. Ramp-Rate Constraints

In practical power systems, generating units cannot change their output instantaneously due to thermal and mechanical limitations. Therefore, ramp-rate constraints are incorporated into the OPF formulation.
The effective operating limits of generator i are defined as

$$P_{Gi}^{min,eff} = \max\left(P_{Gi}^{min}, P_{Gi}^{0} - DR_i\right), P_{Gi}^{max,eff} = \min(P_{Gi}^{max}, P_{Gi}^{0} + UR_i)$$

Where P_{Gi}^{0} is the previous operating output, UR_i is the ramp-up limit, DR_i is the ramp-down limit.
The generator output must satisfy

$$P_{Gi}^{min,eff} \le P_{Gi} \le P_{Gi}^{max,eff}$$

Incorporating ramp-rate limits ensures realistic and feasible dispatch schedules under varying load conditions.

E. Constrained OPF Formulation

The OPF problem can be generally represented as

$$\min; F(X, U)$$

subject to

$$g(X, U) = 0, \qquad h(X, U) \le 0$$

Where X denotes dependent variables, U denotes control variables, g(X,U) represents equality constraints, h(X,U) represents inequality constraints.
The resulting optimization problem is nonlinear, non-convex, and highly constrained, necessitating the use of an efficient metaheuristic optimization technique. In this work, the Gravitational Search Algorithm is employed to obtain the optimal solution while satisfying all operational constraints.

III. STATIC VAR COMPENSATOR MODELING AND OPTIMAL PLACEMENT

A. Static Var Compensator Modeling

A static var compensator (SVC) is a shunt-connected FACTS device that provides fast and continuous reactive power compensation to maintain acceptable voltage levels and enhance system stability. In the exchange of reactive power with the network, the SVC can be used to regulate the voltage, reduce transmission losses, and increase power transfer capability. In this work, we model the SVC as a controllable reactive power injection source connected to a load bus. The reactive power injected or absorbed by the SVC is taken in as follows:

$$Q_{SVC} = V_j^2 B_{SVC}$$

Where Q_{SVC} is the reactive power injected by the SVC, V_j is the voltage magnitude at bus j, and B_{SVC} is the variable susceptance of the SVC. A positive value of B_{SVC} corresponds to capacitive operation, supplying reactive power to the system. A negative value corresponds to inductive operation, where reactive power is absorbed by the network. The operating limits of the SVC are defined as $Q_{SVC}^{min} \le Q_{SVC} \le Q_{SVC}^{max}$ to ensure secure and practical operation.

B. Optimal Location of SVC

The effectiveness of an SVC depends on the location of installation. As the SVC is placed too far from the source, it can provide low voltage support and not enough power. Hence, an appropriate location needs to be found before reactive power compensation is performed. In this work, the optimal location of the SVC is found by voltage deviation analysis. First, the OPF problem is solved without SVC compensation, and the voltage magnitudes of all load buses are evaluated. The bus with the largest voltage deviation from the reference value is found as the weakest bus and is selected for SVC installation.

C. Integration of SVC into OPF

The procedure for the placement of the SVC is as follows:

1. Solve the OPF problem without SVC compensation.
2. Obtain the voltage magnitudes of all the system buses.
3. Compute the bus voltage deviations from the nominal value.
4. Identify the bus where the deviation is the largest.
5. Install the SVC at the identified weak bus.
6. Re-run the OPF including SVC compensation.
7. Evaluate improvements in voltage profile, power loss, and operating costs.

Based on the voltage deviation analysis of the IEEE 14-bus system, Bus-14 is identified as the weakest bus and is thus the best location for installing SVCs. SVC compensation is then incorporated as an additional control variable in the OPF system. Integrate SVC into OPF. We consider the SVC reactive power injection as a control variable during the optimization.

The modified control vector is given by $U = [P_G,;V_G,;T,;Q_C,;Q_{SVC}]$. where P_G denotes generator active powers, V_G denotes generator voltage magnitudes, T denotes transformer tap settings, Q_C represents shunt reactive power sources, and Q_{SVC} represents SVC reactive power compensation. Including SVC compensation in the OPF problem allows for flexibility and contributes to improving voltage profile, reactive power support, and transmission loss reduction while satisfying all system operating constraints.

IV. GRAVITATIONAL SEARCH ALGORITHM-BASED OPF FRAMEWORK

The Optimal Power Flow (OPF) problem is solved using Gravitational Search Algorithm (GSA), a population-based metaheuristic optimization based on Newton's law of gravitation. Each agent is a candidate solution of the OPF problem with generator output, voltage of transformer tap, reactive power source and compensation of SVC. The quality of each solution is checked in the objective function and agents that are more fit are attracted to other agents more strongly. The position vector of the ith agent is

$$X_i = [P_G, V_G, T, Q_C, Q_{SVC}]$$

The gravitational constant is updated as

$$G(t) = G_0 e^{-\alpha t/T}$$

Here, G_0 is the initial gravitational constant, α is the decay coefficient and T is the maximum number of iterations. The mass of each agent is calculated according to the fitness value and the resultant gravitational force acting on the agent is calculated. The acceleration, velocity and position of each agent are updated iteratively according to Newton's motion equations until the termination condition is satisfied. The proposed GSA-based OPF framework has been implemented in Fig. 1. The algorithm begins with OPF formulation, operational and ramp-rate constraints, and the optimal placement of SVC. The candidate solutions are then optimized by iteratively updating mass, force, acceleration, velocity and position. The search is continued until the maximum number of iterations has been achieved to find the optimal operating point with minimum objective function value while satisfying all the system constraints.

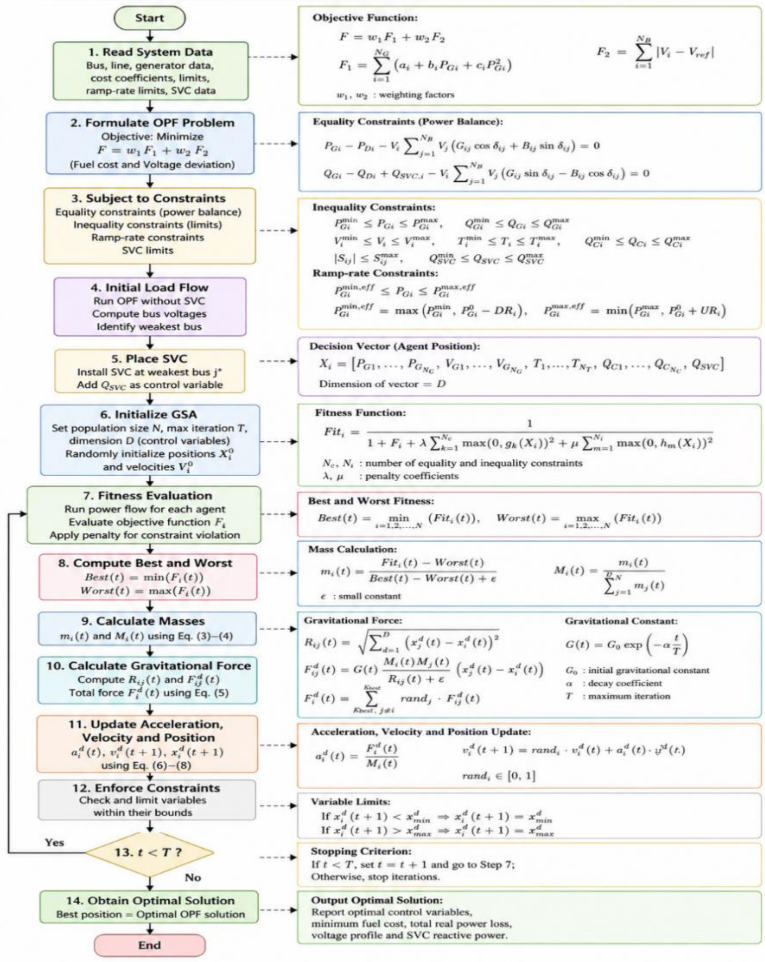

Fig. 1 Flowchart of the proposed GSA-based optimal power flow framework incorporating ramp-rate constraints and optimal SVC placement

V. RESULTS AND DISCUSSION

The effectiveness of the proposed GSA-based OPF framework on the IEEE 14-bus test system was evaluated. The simulation studies were carried out to evaluate the performance of the proposed method in terms of fuel cost minimization, power loss reduction, voltage profile enhancement and convergence characteristics. The simulation parameters used for the analysis are summarized in Table 1.

TABLE.1 INPUT PARAMETERS FOR TEST EXAMPLES

Parameter	PSO	GSA
Population Size	50	50
Maximum Iterations	100	100
ωmax	0.9	–
ωmin	0.4	–
c1, c2	2, 2	–
Initial Gravitational Constant (G0)	–	100
Decay Constant (α)	–	5
ε	–	8.854×10^{-12}
Rnorm	–	2
Test System	IEEE 14-Bus	IEEE 14-Bus
Objective	Fuel Cost & Voltage Deviation	Fuel Cost & Voltage Deviation
SVC	Included	Included
Ramp-Rate Constraints	Considered	Considered

A. Fuel Cost Minimization

The convex fuel cost function is considered as the first objective to validate the performance of our algorithm. The OPF results obtained from PSO and GSA are shown in Table 2. From Table 2, we can see that the proposed GSA has a lower total generation cost of 713.06 $/h compared to 714.24 $/h obtained by PSO. Also, the real power loss is reduced from 7.95 MW to 7.54 MW. The computational time is also significantly reduced from 43.83 s to 25.13 s which indicates the efficiency of our proposed method.

TABLE.2 COMPARISON OF OPF RESULTS FOR IEEE 14 BUS SYSTEM

S. No.	Parameter	Existing PSO Method	Proposed GSA Method
1	**Real Power Generation (MW)**		
	Pg1	172.86	170.94
	Pg2	46.12	47.68
	Pg3	20.48	20.85
	Pg6	16.15	16.53
	Pg8	10.76	10.95
2	**Generator Voltages (p.u.)**		
	Vg1	1.1000	1.1000
	Vg2	0.9482	1.0843
	Vg3	1.0021	1.0617
	Vg6	1.0634	1.0785
	Vg8	0.9416	1.0284
3	**Transformer Tap Settings**		
	T4–7	0.9615	0.9642
	T4–9	0.9448	0.9925
	T5–6	0.9684	1.0036
4	**Shunt Compensator (MVAr)**		
	QC9	26.84	20.12
5	Total Real Power Generation (MW)	266.37	265.95
6	Total Real Power Loss (MW)	8.02	7.46
7	Total Generation Cost ($/h)	715.18	712.84
8	Computing Time (s)	44.36	24.87

A. Optimal SVC Location Identification

To determine the best location of the SVC, we investigated the voltage deviation without compensation of the SVC. The bus voltage magnitudes and voltage deviations are shown in Table 3. The variation of the voltage deviation at different buses is shown in Fig. 3. The highest voltage deviation of Bus-14 is 0.0216 p.u., which means that Bus-14 is the weakest bus in the network. Therefore, Bus-14 was chosen as the ideal location for SVC installation. The chosen location provides maximum voltage support and allows effective reactive power compensation, thereby improving the overall voltage stability of the system.

TABLE.3 BUS VOLTAGE MAGNITUDES AND DEVIATIONS FOR CASE-1

S. No.	Bus Number	Voltage magnitude (p.u)	Voltage deviation (p.u)
1	1	1	0
2	2	1.0095	0.0095
3	3	1.0003	0.0003
4	4	0.9946	0.0054
5	5	0.9974	0.0026
6	6	1.0158	0.0158
7	7	1	0
8	8	1	0
9	9	0.9995	0.0005
10	10	0.9945	0.0055
11	11	1.0012	0.0012
12	12	1.0001	0.0001
13	13	0.9947	0.0053
14	14	0.9784	0.0216

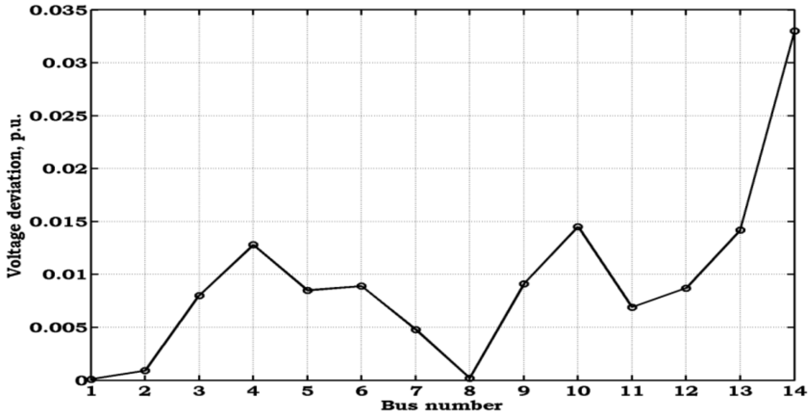

Fig.3 Variation of voltage deviation at system buses in Case-1

B. Voltage Deviation Minimization

The voltage deviation objective was investigated under three different operating situations:

- Case 1: without SVC and without ramp-rate constraints.
- Case 2: without SVC and with ramp-rate constraints.
- Case 3: with SVC and with ramp-rate constraints.

The OPF results are summarized in Table 4. From Table 4, we can see that the presence of ramp-rate constraints slightly influences the operating conditions of the system as we have some restrictions on the generator output. However, when the SVC is incorporated in case 3, additional reactive power support is provided to the network and hence the voltage regulation is better and transmission losses are lower. The SVC injects 0.03584 p.u. reactive power and hence the system performance is improved.

TABLE.4 OPF RESULTS WITH VOLTAGE DEVIATION OBJECTIVE FOR IEEE 14 BUS SYSTEM

S. No.	Parameter	Case-1	Case-2	Case-3 (with SVC)
1	**Real Power Generation (MW)**			
	Pg1	71.02	70.84	66.15
	Pg2	98.12	101.86	100.92
	Pg3	31.54	33.12	36.84
	Pg6	30.41	25.47	24.63
	Pg8	32.09	31.82	35.08
2	**Generator Voltages (p.u.)**			
	Vg1	1.0002	1.0005	1.0010
	Vg2	1.0098	1.0118	1.0134
	Vg3	1.0003	1.0002	1.0004
	Vg6	1.0228	1.0241	1.0368
	Vg8	1.0001	1.0003	1.0006
3	**Transformer Tap Settings (p.u.)**			
	T4–7	0.9898	0.9867	0.9924
	T4–9	0.9702	0.9661	0.9642
	T5–6	0.9889	0.9862	0.9881
4	**Shunt Compensator (MVAr)**			
	QC9	20.18	18.54	18.73
5	SVC Compensation (p.u.)	–	–	0.0365
6	Total Real Power Generation (MW)	263.18	263.11	263.62
7	Total Real Power Loss (MW)	4.36	4.42	4.01
8	Total Generation Cost ($/h)	992.46	996.18	1008.74
9	Voltage Deviation (p.u.)	0.0684	0.0739	0.0691

C. Voltage Profile Analysis

The bus voltage magnitudes obtained for the three operating cases are compared in Table 5. The results indicate that the inclusion of ramp-rate constraints causes slight variations in bus voltages due to limitations on generator dispatch. However, after installing the SVC at Bus-14, the voltage profile is improved across the network.

Particularly, the voltages of the load buses are maintained closer to the nominal value of 1.0 p.u., confirming the effectiveness of reactive power support provided by the SVC. The improvement in voltage profile demonstrates the capability of the proposed framework to simultaneously address economic and voltage stability objectives.

TABLE.5 BUS VOLTAGES OF IEEE-14 BUS SYSTEM

	Voltages		
Bus No	**Case1**	**Case2**	**Case3**
1	1	1.0004	1.0008
2	1.0095	1.0114	1.0131
3	1.0003	1.0001	1.0001
4	0.9946	0.9932	0.9953
5	0.9974	0.996	0.998
6	1.0158	1.0159	1.0158
7	1	1.0002	1
8	1	1.0001	1.0003
9	0.9995	0.9988	1
10	0.9945	0.994	0.9949
11	1.0012	1.0011	1.0016
12	1.0001	1.0001	1.0001
13	0.9947	0.9948	0.9949
14	0.9784	0.978	0.9787

VI. CONCLUSION

We proposed a Gravitational Search Algorithm (GSA)-based Optimal Power Flow (OPF) framework incorporating generator ramp-rate constraints and the optimal selection of SVC placement in this paper. The OPF problem was designed to reduce generation fuel cost and voltage deviation while keeping the system equality and inequality constraints satisfied. The voltage deviation analysis identified Bus-14 as the best site for the installation of SVC. The proposed GSA was applied to determine the optimal control variable settings for the IEEE 14-bus system. In simulation, the proposed method was found to reduce the cost of generation, real power loss, and improve the voltage profile compared to the PSO method. The convergence analysis also showed that GSA provides faster convergence and better search capabilities for constrained OPF problems. The use of SVC compensation was able to improve voltage regulation by providing reactive power support, and the ramp-rate constraints were applied to guarantee reliable and feasible generator operation. The results of this work show that the proposed GSA-based OPF framework can be an effective and computationally efficient tool for the optimization of power systems. Future work will focus on the application of the methodology on large power systems, on integrated renewable energy networks, and for the problem of multi-objective OPF in economics, environment, and security.

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