Optimal Reactive Power Dispatch Through Minimization of Real Power Loss and Voltage Deviation

Ravi Ucheniya, Amit Saraswat and Shahbaz Ahmed Siddiqui

Abstract Optimal reactive power dispatch plays an important role to reduce the total active power losses in transmission lines and the total voltage deviation at the load buses. Optimal reactive power dispatch is a nonlinear, nonconvex, non differentiable, and multimodal optimization problem with discrete and continuous control variables. In this paper, the interface between MATLAB and DigSILENT PowerFactory software has been realized to solve the optimal reactive power dispatch problem. The power flow calculation has been executed on DigSILENT PowerFactory software, and the process of optimization through Genetic Algorithm has been implemented on MATLAB. The proposed approach has been tested on standard IEEE 30 bus system. The results obtained by the proposed approach has been compared with results presented in the literature.

Keywords Optimal Reactive Power Dispatch (ORPD) · DigSILENT PowerFactory · MATLAB and genetic algorithm

Nomenclature

P_{loss} and VD	Total real power loss in transmission lines and total voltage deviation, respectively
N_{Bus}, N_{Tap}, N_{Cap}, N_{Gen}, N_{Tline} and N_{PQ}	Number of buses, tap changing transformer, shunt compensation, generators,

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	transmission lines, and PQ or load buses, respectively
g_k	Conductance of kth transmission line
V_i, V_j and V_k	Voltage magnitude of ith, jth and kth bus, respectively
δ_i and δ_j	Angle of ith and jth bus, respectively
V_k^{sp}	Specified voltage of the kth bus
P_{G_i}	Real power generation through ith generator
P_{D_i}	Real power demand at ith load bus
Q_{G_i}	Reactive power generation through ith generator
Q_{D_i}	Reactive power demand of the ith load bus
G_{ij} and B_{ij}	Conductance and susceptance of the line connected between ith and jth bus
$V_{G_i}^{\min}$ and $V_{G_i}^{\max}$	Minimum and maximum limit of the voltage of the ith generator
$P_{G_i}^{\min}$ and $P_{G_i}^{\max}$	Minimum and maximum limit of the real power generation through ith generator
$Q_{G_i}^{\min}$ and $Q_{G_i}^{\max}$	Minimum and maximum limit of the reactive power generation through ith generator
$T_j^{\min}$ and $T_j^{\max}$	Minimum and maximum limit of the tap setting of the ith tap changing transformer
$Q_{C_i}^{\min}$ and $Q_{C_i}^{\max}$	Minimum and maximum limit of the shunt compensation through ith capacitor
$V_{PQ_i}^{\min}$ and $V_{PQ_i}^{\max}$	Minimum and maximum limit of the voltage of the ith load bus
$S_i^{\max}$	Maximum limit of the power transfer through ith transmission line
x^T and u^T	Vector of control variables and state variables, respectively
PN_1, PN_2, and PN_3	Calculated values of the inequality constraint violations associated with the slack bus active power output, load bus voltage and reactive power output of the all generators
α_{PN_1}, α_{PN_2} and α_{PN_3}	The proposed penalty factor

1 Introduction

Optimal Reactive Power Dispatch (ORPD) is the subcategory of Optimal Power Flow (OPF) optimization framework. In the ORPD, redistribution of reactive power sources (such as the magnitude of the voltage of the generators, transformer's tap position, and value of VAR compensation devices) has been used to reduce total active power losses and total voltage deviation. In literature, many solution methodologies for the ORPD problem have been already proposed and analyzed their performances by various researchers. These solution methodologies may be classified into two broad categories: (a) classical methodologies, and (b) intelligent metaheuristic methodologies [1]. The classical methods are appropriate for single modal optimization problems with decent convergence capabilities. The main drawback of the classical methods is that they are unable to handle the multimodal optimization problems [1]. Whereas, the intelligent metaheuristic optimization methods may be applied to solve the multimodal optimization problems.

The intelligent metaheuristic methodologies may be listed as: Particle Swarm Optimization (PSO) [2], Cataclysmic Genetic Algorithm (CGA) [3], Self-Adaptive Real-Coded Genetic Algorithm (SA-RCGA) [4], Principal Component Analysis (PCA) based Real Coded GA [5], Differential Evolutionary Algorithm (DEA) [6–8], Seeker Optimization Algorithm (SOA) [9], Harmony Search Algorithm (HSA) [10], Biogeography-Based Optimization (BBO) [11], Ant Colony Optimization (ACO) [12], Teaching Learning-Based Optimization (TLBO) and Quasi-Oppositional Teaching Learning-Based Optimization (QOTLBO) [13], PSO with scale-free Gaussian-dynamic [14], etc. Similarly, the hybrid form of these metaheuristic methodologies may be listed as real coded GA and Simulated Annealing (SA) [15], the Multi-Agent System (MAS) and PSO [16], the modified PSO (GA into PSO) and MAS [17], Shuffled Frog Leaping Algorithm (SFLA) and Nelder–Mead (NM) [18], Modified Imperialist Competitive Algorithm (MICA) and Inverse Weed Optimization Algorithm (IWOA) [19], Modified TLBO and Double Differential Evolution (DDE) [20], PSO and Gravitational Search Algorithms (GSA) [21], etc.

In this paper, the interface between MATLAB and DigSILENT PowerFactory software has been used to solve the optimal reactive power dispatch problem [22]. The power flow calculations have been executed on DigSILENT PowerFactory software, whereas the process of optimization through Genetic Algorithm has been implemented on MATLAB. The proposed approach has been tested on standard IEEE 30 bus system. The results obtained by the proposed approach has been compared with the results presented in the literature [21]. Rest of the paper has been organized as follows: the complete mathematical formulation of ORPD problem has been presented in Sect. 2. The flowchart of the proposed approach is presented in Sect. 3. The results obtained from the proposed approach are presented in Sect. 4. Finally, the conclusion of the paper is presented in Sect. 5.

2 Problem Formulation

The primary purpose of the ORPD problem is to reduce the total active power losses in the transmission lines and to improve the voltage profile of load buses. The complete mathematical formulation for ORPD is presented below.

2.1 Objective Function

$$P_{\text{loss}} = \sum_{k=1}^{N_{TL}} g_k \left[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j) \right], \forall i \in N_{\text{Bus}}, \forall j \in N_{\text{Bus}} \quad (1)$$

$$VD = \sum_{k=1}^{N_{\text{Bus}}} \left| V_k - V_k^{sp} \right| \quad (2)$$

2.2 System Constraints

$$P_{G_i} - P_{D_i} = V_i \sum_{j=1}^{N_{\text{Bus}}} \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right], \quad \forall i, j \in N_{\text{Bus}} \quad (3)$$

$$Q_{G_i} - Q_{D_i} = V_i \sum_{j=1}^{NB} \left[G_{ij} \cos(\delta_i - \delta_j) - B_{ij} \sin(\delta_i - \delta_j) \right], \quad \forall i, j \in N_{\text{Bus}} \quad (4)$$

$$V_{G_i}^{\min} \leq V_{G_i} \leq V_{G_i}^{\max} \, \forall i \in N_{\text{Gen}} \quad (5)$$

$$P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max} \, \forall i \in N_{\text{Gen}} \quad (6)$$

$$Q_{G_i}^{\min} \leq Q_{G_i} \leq Q_{G_i}^{\max} \, \forall i \in N_{\text{Gen}} \quad (7)$$

$$T_j^{\min} \leq T_j \leq T_j^{\max} \, \forall j \in N_{\text{Tap}} \quad (8)$$

$$Q_{C_i}^{\min} \leq Q_{C_i} \leq Q_{C_i}^{\max} \, \forall i \in N_{\text{Cap}} \quad (9)$$

$$V_{L_i}^{\min} \leq V_{L_i} \leq V_{L_i}^{\max} \, \forall i \in N_{PQ} \quad (10)$$

$$S_j \leq S_j^{\max} \, \forall j \in N_{\text{Tline}} \quad (11)$$

$$x^T = \left[V_{G_1} \ldots V_{G_{N_{\text{Gen}}}}, Q_{C_1} \ldots Q_{C_{N_{\text{Cap}}}}, T_1 \ldots T_{N_{\text{Tap}}}\right] \tag{12}$$

$$u^T = \left[P_{G_1}, V_{L_1} \ldots V_{L_{N_{PQ}}}, Q_{G_1} \ldots Q_{G_{N_{\text{Gen}}}}\right] \tag{13}$$

2.3 General Formulation of the Objective Function

The final objective function, which is used by the optimization algorithm as given below.

$$\text{minimize } F = F_{OBF} + PN_1\alpha_{PN_1} + PN_2\alpha_{PN_2} + PN_3\alpha_{PN_3} \tag{14}$$

$$PN_1 = \left(P_{G_1} - P_{G_1}^{\lim}\right)^2, \quad \alpha_{PN_1} = (PN_1 + 1) \tag{15}$$

$$PN_2 = \sum_{i=1}^{NL}\left(V_{L_i} - V_{L_i}^{\lim}\right)^2, \quad \alpha_{PN_2} = (PN_2 + 1) \tag{16}$$

$$PN_3 = \sum_{i=1}^{NG}\left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2, \quad \alpha_{PN_3} = (PN_3 + 1) \tag{17}$$

3 Solution Methodology

The flow chart of the proposed approach has been presented in Fig. 1. In this paper, two modification has been proposed: one is "MIN MAX modification" and second is "Violation of the Constraints Penalize by itself". In MIN MAX modification, the minimum value of the control variables are set as the "base value" and the difference between the upper and lower boundary of the control variables are set as the "difference value". Now, the new setting of the upper and lower limit of the control variables are "1" and "0", respectively. GA performs optimization process using newly defined range of control variables.

In second modification, violations of control variables as depicted in Eq. (12) have restricted by the lower and upper limit of the control variables. Similarly, violation of the state variables as depicted in Eq. (13) have been restricted by penalty based objective function as depicted in Eq. (14). Penalty function approach has been used to handle the violation of the inequality constraint [5]. The violation of the constraints has been penalized by the proposed penalty factor. The formulation of the proposed penalty factors is presented in Eqs. (15–17). PN_1, PN_2 and PN_3 are the measurement of the violation of the state variables and α_{PN_1}, α_{PN_2} and α_{PN_3} are the penalty factor, respectively.

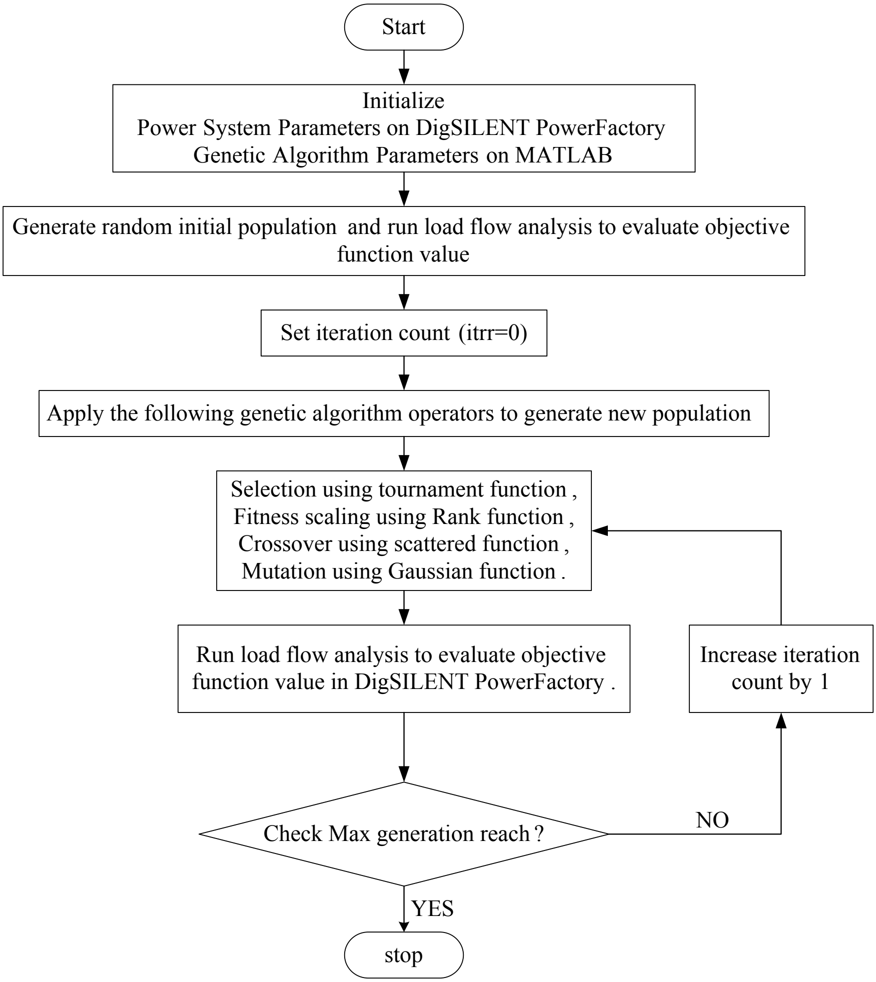

Fig. 1 Flowchart of the interface between GA and DigSILENT PowerFactory

4 Simulation Result

In this section, the proposed approach has been tested on standard IEEE 30 bus system. The IEEE 30 bus system data and limits of control and state variables are adapted from [21]. The total active power demand of the system is 2.834 p.u. at 100 MVA base. In this paper, 30 individual test runs have performed to validate the proposed approach. Results obtained by the proposed approach have been compared with those reported in [21]. The target objectives, those are presented by Eq. (1)

Table 1 Comparison of results for case 1

Variable	Initial base [21]	PSO [21]	GSA [21]	The proposed approach
V_{g1}	1.05	1.1	1.1	1.1
V_{g2}	1.04	1.0944	1.0944	1.0946
V_{g5}	1.01	1.075	1.0748	1.0757
V_{g8}	1.01	1.0767	1.0768	1.0764
V_{g11}	1.05	1.1	1.1	1.1
V_{g13}	1.05	1.1	1.1	1.0998
$T_{6–9}$	1.078	1.0473	1.0399	1.0375
$T_{6–10}$	1.069	0.9	0.9	0.907
$T_{4–12}$	1.032	0.9831	0.9827	0.9793
$T_{28–27}$	1.068	0.9664	0.9699	0.9667
Q_{c10}	0	5	3.5717	4.9998
Q_{c12}	0	5	3.0984	4.9247
Q_{c15}	0	5	3.2925	4.9268
Q_{c17}	0	5	4.0166	4.9922
Q_{c20}	0	3.4023	3.0309	4.0713
Q_{c21}	0	5	4.0339	4.9697
Q_{c23}	0	5	2.9946	2.8126
Q_{c24}	0	5	4.3499	4.9872
Q_{c29}	0	2.1038	2.6902	2.361
P_{loss} (in MW)	5.8223	4.5388	4.5515	**4.5323**
% reduction	0	22.04	21.83	**22.16**

(case 1) and Eq. (2) (case 2) and formulated as Eq. (14), have been solved using the proposed approach. The comparison of the results obtained by proposed approach and results reported in [21] are presented in Tables 1 and 2. The convergence graph of the target objectives is depicted in Fig. 2.

It is observed from the Table 1 that the proposed approach is able to reduce the total active power losses in the transmission line 4.5323 MW that is 22.16% from the initial value 5.8223 MW in comparison to 22.04% with PSO [21], 21.83% with GSA [21]. Also, it is observed from the Table 2 that the proposed approach is able to reduce the total voltage deviation 0.1002 pu that is 91.29% from the initial value 1.1497 pu in comparison to 91.26% with PSO [21], 88.77% with GSA [21]. The statistical analysis in terms of Best, Worst and Standard Deviation (SD) for Case 1 (i.e. power loss minimization) and Case 2 (i.e. voltage deviation minimization) are listed in Tables 3 and 4, respectively.

Table 2 Comparison of result for case 2

Variable	Initial (base) [21]	PSO [21]	GSA [21]	The proposed approach
V_{g1}	1.05	1.0264	1.0374	1.0307
V_{g2}	1.04	1.0162	1.04	1.0234
V_{g5}	1.01	1.0185	1.022	1.0183
V_{g8}	1.01	0.9987	1.0047	1.0003
V_{g11}	1.05	1.0427	0.9885	1.019
V_{g13}	1.05	0.9965	0.9924	1.0004
$T_{6–9}$	1.078	1.0598	0.9772	1.0298
$T_{6–10}$	1.069	0.9144	0.9	0.9074
$T_{4–12}$	1.032	0.958	0.9274	0.9597
$T_{28–27}$	1.068	0.9758	0.9612	0.968
Q_{c10}	0	4.9995	1.9778	4.7364
Q_{c12}	0	0	0.424	0.1194
Q_{c15}	0	5	2.2268	4.4796
Q_{c17}	0	4.9958	2.8945	2.0072
Q_{c20}	0	5	4.0503	4.9906
Q_{c21}	0	5	3.2996	4.9921
Q_{c23}	0	4.9988	2.5926	4.9121
Q_{c24}	0	5	2.6791	4.8805
Q_{c29}	0	4.9994	2.8961	3.1536
VD (in p.u.)	1.1497	0.1005	0.1291	**0.1002**
% reduction	0	91.26	88.77	**91.29**

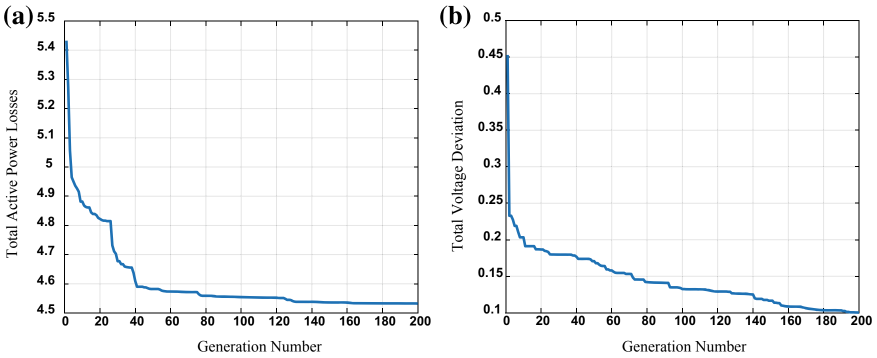

Fig. 2 Convergence of the total active power loss (**a**) and voltage deviation (**b**) in IEEE 30 bus power system using the proposed optimization method

Table 3 Comparison of best, worst, and standard deviation (SD) for case 1

Case 1	PSO [21]	GSA [21]	The proposed approach
Best	4.5388	4.5515	4.5323
Worst	5.1327	4.6408	4.9215
SD	0.204	0.024	0.1001

Table 4 Comparison of best, worst, and standard deviation (SD) for case 2

Case 2	PSO [21]	GSA [21]	The proposed approach
Best	0.1005	0.1291	0.1002
Worst	0.1672	0.1884	0.1484
SD	0.0221	0.0164	0.0127

5 Conclusion

In this paper, the ORPD problem has been successfully solved by the proposed GA based optimization approach. ORPD is a nonlinear, nonconvex, non differentiable, and multimodal problem with a discrete and continuous control variable. In this study, two different objective functions such as total active power loss in the transmission line and total voltage deviation on load buses have been minimized subjective to different equality and inequality constraints for IEEE 30 bus power system. In addition, the interface between GA and DigSILENT PowerFactory software has been realized efficiently to solve the ORPD problem. The obtained results demonstrate the potential and effectiveness of the proposed approach.

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