OPTIMAL REACTIVE POWER DISPATCH USING THE MATLAB OPTIMIZATION TOOLBOX

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Abstract— **Optimal Reactive Power Dispatch (ORPD) is required for power system control and proper operation. ORPD reduces the power system losses and improves the voltage profile, power system security, power transmission capability and overall system operation. The reactive power control variables like generator voltage, transformer tap-settings and switchable VAR sources are adjusted to solve ORPD problem. In this paper, the ORPD problem is solved as nonlinear constrained optimization problem with equality and inequality constraints for minimization of power losses and voltage deviation. The proposed approach employs Optimization toolbox of Matlab for the optimal setting of ORPD control variables. The Optimization toolbox has been implemented on a standard IEEE 30-bus system to minimize power losses and voltage deviation. The simulation results of the proposed approach are compared with the results obtained from differential evolution(DE) based algorithm.**

Index terms— **fmincon, optimal reactive power dispatch, power loss, voltage deviation**

I. INTRODUCTION

In a power system, the minimization of the power loss in transmission lines and voltage deviation at the load buses can be obtained by controlling the reactive power, referred as optimal reactive power dispatch (ORPD).A sub-problem of optimal power flow (OPF) calculation is called Optimal reactive power dispatch. A nonlinear programming problem (NLP) that is used to find out the optimal control parameters/ circumstance to minimize or maximize a desired objective function, subject to certain equality and inequality constraints is called optimal power flow. Carpentier [1] introduced the OPF in 1960s. A set of control variables like generator voltage magnitudes, switchable VAR sources and transformer tap setting is provided by the Solution of ORPD problem for the power system operator to maintain load bus voltage within desired limits and to minimize transmission losses by rescheduling power flows.

In the past two decades, the problem of ORPD for improving economy and security of power system operation has received much attention. In recent years, the problem of ORPD for control of the voltage and for reduction of the power losses has received much attention [2].The minimization of the real power losses and to improve the voltage profile by redistribution of reactive power in the system are the main objective of ORPD [3]. The various optimization algorithm are used for the solution of such type of problem. These algorithms can be classified into three groups, namely Nonlinear Programming, sensitivity analysis / gradient-based optimization, and heuristic methods [3-7]. ORPD studies are performed more and more by engineers, but further applications ranging from planning, operation and control of modern power systems are of great importance and hence must be investigated [8]. In order to speed up the research of such those applications, researchers have put attention on commercial software packages for solving a large variety of OPF problems including ORPD.

Nowadays, OPF models are solved by using commercial software packages AMPL [9] and GAMS [10]. To solve an OPF model with complimentary constraints, the AMPL software has been employed [11], and voltage stability constraints in order to control voltage stability (VS) of a power system [12]. By using the Optimization toolbox of matlab, Implementation and solution of a conventional ORPD problem is presented in this paper [14].

Fmincon from Optimization toolbox of Matlab has been proposed here. This technique can take care of optimality on rough, discontinuous and multi-modal surfaces. The advantages of this method are, its convergence is very fast than other techniques, its coding is easy to use and it can handle constrained and unconstrained optimization.

II. RPD PROBLEM FORMULATION

The objective of ORPD is to determine the reactive power control variables, which minimizes the objective functions. This is mathematically stated as follows:

A. *Problem objectives*

In this study, the following objectives are considered:

1. *Minimization of system power losses*

The minimization of system real power losses Ploss can be calculated as follows:

$$F1 = Ploss = \sum_{k=1}^{nl} g_k[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \quad (1)$$

where nl is the number of transmission lines; gk is the conductance of the kth line; Vi and Vj are the voltage magnitude at the end buses i and j of the kth line, respectively, and ıi and ıj are the voltage phase angle at the end buses i and j.

$$f1 = Ploss = \sum_{k=1}^{nl} g_k[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \quad (1)$$

2. Voltage profile improvement

The most important security and service quality indices is called Bus voltage. voltage profile improvment can be obtained by minimizing the load bus voltage deviations from 1.0 per unit. The objective function can be expressed as:

$$f2 = VD = \sum_{i \in NL} |V_i - 1.0| \quad (2)$$

where NL is the number of load buses.

A. ORPD PROBLEM CONSTRAINTS

The reactive power optimization problems subjected to the following equality and inequality constraints.

1. Equality constraints

Here the equality constraints are the real and reactive power balance equations and are represented as follows:

$$P_{Gi} - P_{Di} - V_i\sum_{j=1}^{NB} V_j[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] = 0 \quad (3)$$

$$Q_{Gi} - Q_{Di} - V_i\sum_{j=1}^{NB} V_j[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] = 0 \quad (4)$$

Where i=1......NB; *NB* is the number of buses; P_G and Q_G are the generator active and reactive power. P_D and Q_D are the load active and reactive power. Gij and Bij are the transfer conductance and susceptance between bus i andj,respectively.

B. Inequality constraints

The inequality constraints for ORPD problem are the power system operating constraints and are expressed as follows:

1. Generator constraints:

Generator voltages V_G and reactive power output Q_G are provided by their upper and lower limits as follows :

$$V_{Gi}^{min} \le VGi \le V_{Gi}^{max}, \quad i=1,2,........,NG \quad (5)$$

$$Q_{Gi}^{min} \le QGi \le Q_{Gi}^{max}, \quad i=1.............,NG \quad (6)$$

Where NG is the number of generators.

2. Transformer constraints:

Transformer tap T settings are to be within their minimum and maximum limits as follows:

$$T_i^{min} \le Ti \le T_i^{max}, \quad i=1............NT \quad (7)$$

Where NT is the number of transformers.

3. Shunt VAR constraints:

Shunt VAR compensations are restricted by their limits as follows:

$$Q_{ci}^{min} \le Q_{ci} \le Q_{ci}^{max} \quad i=1.............N_c \quad (8)$$

Security constraints: these include the constraints of voltages at load buses and transmission line loadings as follows:

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \quad i=1..................NL \quad (9)$$

$$S_{li} \le S_{li}^{max} \quad i= 1, . . . , nl \quad (10)$$

The objectives and constraints of the ORPD problem can be mathematically formulated as a nonlinear constrained optimization problem and can be expressed as:

Minimize $[P_L(x,u), VD(x,u)]$ (11)

Subject to;

Equality constraint $g(x,u) = 0$ (12)

and

Inequality constraint $h(x,u) \le 0$ (13)

where x is the vector of dependent variables consisting of load bus voltages V_L, generator reactive power outputs Q_G, and transmission line loadings S_L. Hence, x can be expressed as:

$$x^T = [V_{L1} \ldots V_{NL}, Q_{G1} \ldots Q_{GNG}, S_{L1} \ldots S_{Lnl}] \quad (14)$$

u is the vector of control variables consisting of generator voltages V_G and transformer tap settings T. Thus, u can be expressed as:

$$u^T = [V_{G1} \ldots V_{GNG}, T_1 \ldots T_{NT}] \quad (15)$$

Optimization toolbox of Matlab has been applied for this ORPD problem. This ORPD problem is a combinatorial optimization problem with multi-extremism and non-linear property. In this paper, the ORPD problem has been solved by optimizing the generator voltages and transformer tap-settings. In this paper, the ORPD problem has been solved with 19 control variables using Optimization toolbox and compared with the results obtained from DE based algorithm by optimizing the generator voltages, switchable VAR sources and transformer tap- settings .

III.OPTIMIZATION TOOLBOX

From an optimization point of view, a continuous nonlinear constrained optimization problem is represented by ORPD, which can be solved by using function fmincon of the Matlab optimization toolbox. The *fmincon* function employs a Sequential Quadratic Programming (SQP) optimization algorithm, started with input/output argument to configure the optimization parameters, sets the problem to be optimized and displays the information. The SQP algorithm uses Quadratic

Programming (QP) algorithm and is used to solve a sub-problem based on the quadratic approximation of the Langrangian at each iteration. QP involves minimizing or maximizing an objective function subject to bounds, linear equality, and inequality constraints [14]. From an optimization point of view, the ORPD problem represents a continuous non linear constrained optimization problem, which can be solved by using the function “fmincon” of that optimization toolbox. This function uses a Sequential Quadratic Programming optimization algorithm, started with input/output arguments to configure the optimization parameters, set the problem to be optimized and display information. As any Matlab function, the *fmincon* function deals with both input I_A and output O_A arguments. The general form of this function is,

$$[O_A]=\text{fmincon}(I_A)$$

where I_A and O_A are sets of input and output arguments, respectively. fmincon uses one of three algorithms: active-set, interior-point, or trust-region-reflective. The `'active-set'` algorithm (formerly called medium-scale) is the default. You can choose the algorithm at the command line with optimset. For example:

Options = optimset('Algorithm','active-set')

IV.RESULTS AND DISCUSSION

The optimization toolbox based approach has been tested on the standard IEEE 30-bus system [2]. IEEE 30-bus systems have 6 generator buses, 24 load buses and 41 transmission lines shown in fig I. This system has 19- control variables as follows: 6- generator voltage magnitude, 4-tap transformer setting i.e. T11, T12, T15, T36 and 9-switchable VAR. To demonstrate the effectiveness of the results obtained from proposed algorithm, two different cases have been considered and compared with the results of DE [15].

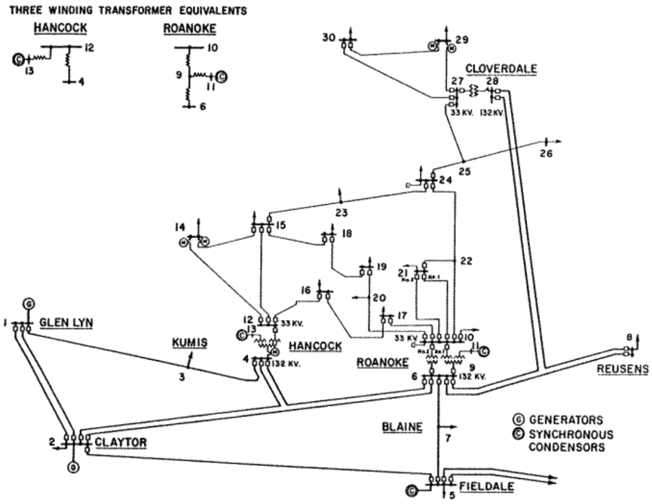


Figure I. IEEE 30-Bus system

Case1: Minimization of system power losses.
Case2: Improvement of voltage profile.

Case 1: (minimization of system power losses)

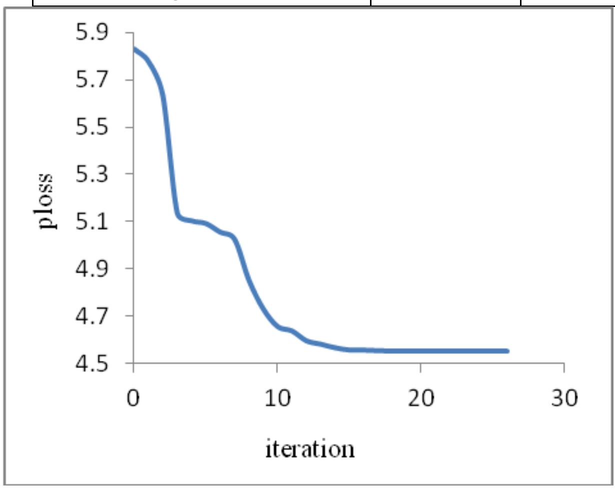
In this case, Optimization toolbox was applied to minimize real transmission line losses as the objective function. The convergence characteristic as obtained using Optimization toolbox has been shown in Fig. II, while Table 1 shows the best result of *Ploss* function when it is optimized individually and is compared with the results obtained from DE algorithm for the same test system. As can be observed from Table1, the proposed Optimization toolbox based approach gives the minimum transmission line losses of 4.5538 MW as compared to the reported results using DE algorithm, which establishes the effectiveness of the proposed Optimization toolbox. Another important feature of the proposed Optimization toolbox is its convergence speed. The DE algorithm [15] required 500 iterations to reach the converged solution, while the Optimization toolbox required only 42 iterations to converge. Thus the proposed approach is found to be superior from the view point of convergence speed.

Table I
SETTING OF CONTROL VARIABLE FOR *Ploss* MINIMIZATION

Figure II. Convergence characteristic for *Ploss* Minimization

Case2: (improvement of voltage profile)

S.No.	Control Variable	Setting	
		DE[15]	FMINCON
1	V1	1.0100	1.0043
2	V2	0.9918	0.9547
3	V5	1.0179	1.0159
4	V8	1.0183	1.0359
5	V11	1.0114	1.0548
6	V13	1.0282	1.0111
7	T11	1.0265	1.0760
8	T12	0.9038	0.9015
9	T15	1.0114	0.9888
10	T36	0.9635	0.9671
11	Q_{C10}	0.0494	0.0494
12	Q_{C12}	0.0108	0.0482
13	Q_{C15}	0.0499	0.0496
14	Q_{C17}	0.0023	0.0000
15	Q_{C20}	0.0499	0.0500
16	Q_{C21}	0.0490	0.0495
17	Q_{C23}	0.0498	0.0495
18	Q_{C24}	0.0496	0.0485
19	Q_{C29}	0.0223	0.0258
Power Loss(MW)		6.4755	5.9173
Voltage Deviation		**0.0911**	**0.0904**



In this case, Optimization toolbox was applied for improvement of voltage profile. The convergence characteristic as obtained for this case is shown in Fig. III, while Table 2 shows the best result of *VD* function when it is optimized individually and is compared with the results obtained from DE algorithm for the same test system. As can be observed from Table2, the proposed Optimization toolbox

S.No.	Control Variable	Setting	
		DE[15]	FMINCON
1	V1	1.1000	1.1000
2	V2	1.0931	1.0943
3	V5	1.0736	1.0747
4	V8	1.0756	1.0767
5	V11	1.1000	1.1000
6	V13	1.1000	1.1000
7	T11	1.0465	1.0587
8	T12	0.9097	0.9000
9	T15	0.9867	0.9935
10	T36	0.9689	0.9732
11	Q_{c10}	0.0500	0.0500
12	Q_{c12}	0.0500	0.0500
13	Q_{c15}	0.0500	0.0500
14	Q_{c17}	0.0500	0.0500
15	Q_{c20}	0.0440	0.0500
16	Q_{c21}	0.0500	0.0500
17	Q_{c23}	0.0280	0.0398
18	Q_{c24}	0.0500	0.0500
19	Q_{c29}	0.0259	0.0310
Power Loss(MW)		**4.5550**	**4.5538**
Voltage Deviation		1.9589	1.8783

based approach gives the minimum voltage deviation of 0.0904 MW as compared to the reported results using DE algorithm, which establishes the effectiveness of the proposed Optimization toolbox. For this case, the voltage deviation is minimized, reaches to a value of 0.0904.The comparison from the Optimization toolbox gives the best result for voltage deviation than DE. The DE algorithm [15] required 500 iterations to reach the converged solution, while the Optimization toolbox required only 67 iterations to converge. Thus the Optimization toolbox is found to be more superior from the view point of convergence speed.

V. CONCLUSION

In this paper, Optimization toolbox of Matlab has been proposed, developed, and successfully applied to solve optimal reactive power dispatch (ORPD) problem. The ORPD problem has been formulated as a constrained optimization problem to minimize power losses and to improve the voltage profile. Standard IEEE-30 bus test system is considered to test and examine the proposed approach. The results show the effectiveness and better performance of the proposed algorithm to solve ORPD problem. The results are compared with results obtained from DE based algorithm. The comparison shows the effectiveness and fast calculation of the

Bus no.	Load		Bus no.	Load	
	P (p.u.)	Q(p.u.)		P(p.u.)	Q(p.u.)
1	0.000	0.000	16	0.035	0.018
2	0.217	0.127	17	0.090	0.058
3	0.024	0.012	18	0.032	0.009
4	0.076	0.016	19	0.095	0.034
5	0.942	0.190	20	0.022	0.007
6	0.000	0.000	21	0.175	0.112
7	0.228	0.109	22	0.000	0.000
8	0.300	0.300	23	0.032	0.016
9	0.000	0.000	24	0.087	0.067
10	0.058	0.020	25	0.000	0.000
11	0.000	0.000	26	0.035	0.023
12	0.112	0.075	27	0.000	0.000
13	0.000	0.000	28	0.000	0.000
14	0.062	0.016	29	0.024	0.009
15	0.082	0.025	30	0.106	0.019

proposed approach over the DE based approach in terms of solution quality.

Table II

SETTING OF CONTROL VARIABLE FOR VD MINIMIZATION

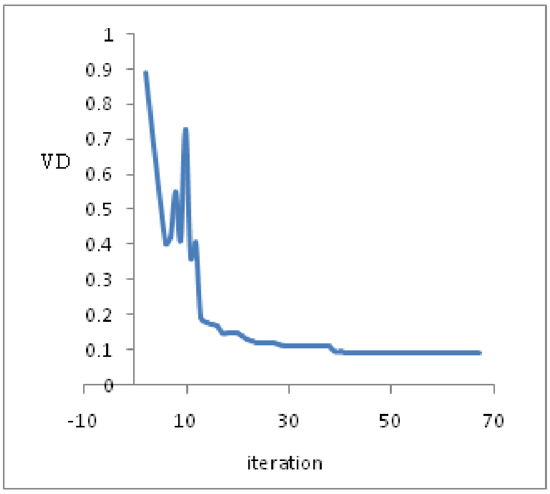


Figure III. Convergence characteristic for VD Minimization

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Appendix A.

For power loss and voltage deviation evaluation, the bus voltage and network information provided by the load flow program. Data for IEEE- 30 bus test system are given in Tables A1-A3.

Table A1
Load data

Line no.	From bus	To bus	Line impedance	
			R(p.u)	X(p.u.)
1	1	2	0.0192	0.0575
2	1	3	0.0452	0.1852
3	2	4	0.0570	0.1737
4	3	4	0.0132	0.0379
5	2	5	0.0472	0.1983
6	2	6	0.0581	0.1763
7	4	6	0.0119	0.0414
8	5	7	0.0460	0.1160
9	6	7	0.0267	0.0820
10	6	8	0.0120	0.0420
11	6	9	0.0000	0.0280
12	6	10	0.0000	0.5560
13	9	11	0.0000	0.2080
14	9	10	0.0000	0.1100
15	4	12	0.0000	0.2560
16	12	13	0.0000	0.1400
17	12	14	0.1231	0.2559
18	12	15	0.0662	0.1304
19	14	16	0.0945	0.1987
20	16	15	0.2210	0.1997
21	15	17	0.0824	0.1932
22	18	18	0.1070	0.2185
23	19	19	0.0639	0.1292
24	10	20	0.0324	0.0845
25	10	20	0.0936	0.2090
26	10	17	0.0324	0.0845
27	10	21	0.0348	0.0749
28	21	22	0.0727	0.1499
29	15	22	0.0116	0.0236
30	22	23	0.1000	0.2020
31	23	24	0.1150	0.1790
32	24	24	0.1320	0.2700
33	25	25	0.1885	0.3292
34	25	26	0.2544	0.3800
35	28	27	0.1093	0.2087
36	27	27	0.0000	0.3960
37	27	29	0.2198	0.4153
38	29	30	0.3202	0.6027
39	29	30	0.2399	0.4533
40	8	28	0.6360	0.2000
41	6	28	0.0169	0.0599

Table A2

The minimum and maximum limits for control variables along with the initial settings.

	Min.	Max	Initial
P1	50	200	99.24
P2	20	80	80.0
P5	15	50	50.0
P8	10	35	20.0
P11	10	30	20.0
P13	12	40	20.0
V1	0.95	1.1	1.05
V2	0.95	1.1	1.04
V5	0.95	1.1	1.01
V8	0.95	1.1	1.01
V11	0.95	1.1	1.05
V13	0.95	1.1	1.05
T11	0.9	1.1	1.078
T12	0.9	1.1	1.069
T15	0.9	1.1	1.032
T36	0.9	1.1	1.068

Q_{c10}	0.0	5.0	0.0
Q_{c12}	0.0	5.0	0.0
Q_{c15}	0.0	5.0	0.0
Q_{c17}	0.0	5.0	0.0
Q_{c20}	0.0	5.0	0.0
Q_{c21}	0.0	5.0	0.0
Q_{c23}	0.0	5.0	0.0
Q_{c24}	0.0	5.0	0.0
Q_{c29}	0.0	5.0	0.0
Power losses			5.842
VD			1.606

Table A3
Line data

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