A HYBRID METHODOLOGY FOR OPTIMAL VAR DISPATCH IN THE WESTERN ALGERIAN POWER SYSTEM

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This paper describes the methodology adopted for the optimal var dispatch (OVD) integrating a particle swarm optimization (PSO) algorithm and the interior point method (IPM). The proposed hybrid method can be mainly divided in two parts. The first part is to solve the OVD with the IPM based on the logarithmic- barrier primal-dual algorithm (LB-PDA), for non linear programming (NLP) by relaxing the discrete variables. In the second part, the PSO algorithm is used to solve the discrete variables with the continuous variables being fixed, whereas the IPM solves the continuous optimization with the discrete variables being constant. The optimal solution can be obtained by solving the two sub-problems alternately. Numerical simulation on the Western Algerian power system illustrate this proposed hybrid method.

1. INTRODUCTION

The purpose of OVD is mainly to improve the voltage profile in the system and to minimize the total active power losses while satisfying the physical and operational constraints. This goal is achieved by proper adjustment of reactive power control variables like generator bus voltage magnitude, transformer tap settings, and shunt reactive power sources (capacitor and reactor bank, static var compensator – SVC – etc.). To solve the OVD problem, a number of conventional optimization techniques [1–2], have been proposed. These include the Newton method, Non-linear Programming, Quadratic Programming, and Interior point method.

Although these techniques have been successfully applied for solving the OVD, still some difficulties are associated with them. One of the difficulties is the multimodal characteristic of the problems to be handled. Also, due to the non-

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differential, non-linearity and non-convex nature of the OVD problem, most of the techniques converge to a local optimum. Evolutionary computation techniques like Genetic Algorithm (GA) [3], Evolutionary Programming techniques [3], Evolutionary Strategy [4] and Hybrid method [5], have been applied to solve this kind of problems in recent years.

In this paper, a hybrid methodology based on the IPM for solving the continuous variables and the PSO algorithm to determine the discrete variables alternately has been proposed to solve the OVD problem. The efficiency of this methodology is assessed by means of its application to the western Algerian transmission/sub-transmission network.

The PSO approach is inspired by the behaviour of birds assembling into clouds, fish benches under water or displaced swarms of bees. It is a stochastic optimization technique based on a population, developed by Kwang and El-sharkawi in [6]. The system is initialized with a population of random solutions, and it therefore seeks optimum by providing generations all like genetic algorithms. It is relatively a new family of algorithms that may be used to find optimal (or near optimal) solutions to numerical problems. The potential solutions, called particles, move in the definite space of the studied problem while following the existing optimal particles.

The IPM is a very efficient technique when the feasible region is defined by inequality constraints. Karmarkar (1984) was a precursor in implementing the first efficient algorithm. The projective method can be compared to the Simplex algorithm in application on practical problems. The IPM have gained people's recognition with the advantages of fast convergence and powerful robustness and customized solution. The application of IPM to power system problems started in the 1990s. Among the many variants of IPM, the primal-dual interior point method (PD-IPM) is theoretically sound and the most computationally efficient for LP. The IPM has been applied to optimize the operation of power systems with great success, solving problems such as the optimal power flow (OPF), optimal reactive power dispatch, state estimation, voltage stability, hydro-scheduling and security constrained economic dispatch.

By integrating a PSO algorithm with IPM, a hybrid approach for the OVD problem is proposed in this paper.

This paper is organized as follows. First a brief review of the OVD problem formulation is presented. The practical implementations for the IPM and PSO algorithms are reviewed in section 3 and 4. In section 5, the hybrid method integrating the PSO and the IPM is depicted. Section 6 presents numerical results obtained using this methodology on the Algerian network. Finally, section 7 concludes.

2. PROBLEM FORMULATION

The formulation of the OVD problem can be expressed as the following mixed-integer nonlinear programming (MINLP) problem [11]:

$$\begin{array}{ll} \min & f(z) \\ s.t. & g(z) = 0 \\ & z_{\min} \le z \le z_{\max} \end{array} , \tag{1}$$

where $f(z)$ is the objective function, representing the total active power losses; $g(z)$ are equality constraints, representing load flow solution; $z_{\min}$ is the lower limit of variable z ; $z_{\max}$ is the upper limit of variable z .

The variable $z = [x, u_C, u_D]$ is the vector of decision variables including the vector of state variables x (voltage magnitudes and angles of the load buses), the vector of continuous control variables u_C (generator voltages magnitude V_G and SVC voltages magnitude V_{SVC}), and the vector of discrete control variables u_D (reactive power Q_C of the shunt capacitor or reactor and transformer tap ratios t).

3. OVERVIEW FOR IPM

In this paper, a Primal-Dual Interior Point Method (PD-IPM) is described to directly solve the large-scale NLP that represents the total real power loss minimization in a power network. The inequality constraints of (1) are transformed in equality constraints by using non-negative slack variables (z_u, z_l) . Besides the slack variables are included in $f(z)$ as logarithmic terms (logarithmic-Barrier function). In this method, all the decision variables, z in (1), are first assumed to be continuous. The OVD problem can be transformed into the sub-problem of the following Lagrange function without the constraints:

$$L = f(z) - \mu \sum (\ln z_{uj} + \ln z_{ij}) - \lambda^t g(z) - \gamma^t (z_u + z - z_{\max}) - \phi^t (z_l - z + z_{\min}), \tag{2}$$

where λ , γ and ϕ are Lagrange multipliers vector. The barrier parameter $\mu > 0$ and is decreased to zero as the algorithm iteration progresses. Based on the Karush-Kuhn-Tucker (KKT) first-order conditions of the sub-problem, a set of nonlinear algebraic equations is formed and then solved by the Newton-Raphson algorithm [7, 8]. The iteration procedure of the IPM is stopped when the mismatches of KKT conditions are sufficiently small or less than the specified tolerance ε as shown in the following:

$$\| L_z \| = \| \nabla f(z) - \nabla g^t(z)\lambda - \gamma - \phi \| \le \varepsilon_u , \tag{3}$$

$$\| L_\lambda \| = \| g(z) \| \le \varepsilon, \tag{4}$$

$$\| L_\gamma \| = \| z_u + z - z_{\max} \| \le \varepsilon, \tag{5}$$

$$\| L_\phi \| = \| z_l - z + z_{\min} \| \le \varepsilon, \tag{6}$$

$$\gamma^t z_u + \phi^t z_l \le \varepsilon. \tag{7}$$

In the primal-dual theory, z, z_u and z_l are the primal variables; λ, γ and ϕ are the dual variables; equation (3) is the dual feasible conditions; Equations (4), (5) and (6) are the primal feasible conditions; and (7) is the complementary slackness condition. Therefore, the optimal solution fulfills the stopping criteria in (3–7), while the feasible solution satisfies the stopping criteria in (4–6).

The procedure to solve the KKT of the Logarithmic-Barrier Primal Dual Algorithm (LBPDA) problem can be summarized as follows. First, we assume a starting point that satisfies the positivity condition on the slack variables, and a barrier parameter $\mu > 0$ that causes the objective function logarithmic terms to dominate over the value of the original objective $f(z)$. Second, the KKT equations are solved by one iteration of the Newton's method. Third, all the variables are updated. Fourth, the barrier parameter is appropriately reduced to the next point. This iterative process is repeated until primal and dual feasibilities are achieved within acceptable accuracy, and a stopping criterion is satisfied.

The PD-IPM application, detail and implementation for OVD in electrical power systems are presented in [11].

4. OVERVIEW OF PSO

PSO is one of the evolutionary computation techniques. The method has been developed through simulation of simplified social models. The method is based on swarms such as fish schooling and bird flocking. It was originally developed for optimization problems with continuous variables. However, it is easily expanded to treat problems with discrete variables. The basic assumption behind the PSO algorithm is birds find food by flocking and not individually. This leads to the assumption that information is owned jointly during in flocking. Basically PSO was developed for two-dimension solution space. The position of each particle is represented by its coordinates along the XY axes as well as by the speed, which is expressed by V_x (the speed along the X axis) and V_y (the speed along the Y axis).

The modified position of each particle is carried out by the information of its position and speed (velocity). PSO procedures based on the above concept can be described as follows. Namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (*pbest*) and its *XY* position. Morover, each agent knows the best in the group (*gbest*) among pbests. Each agent tries to modify its position using the current velocity and the distance from pbest and gbest. This modification can be represented by the concept of flight velocity [9–10]. Velocity of each agent can be modified by following equation:

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand_1 \times (pbest_i - S_i^k) + c_2 \times rand_2 \times (gbest - S_i^k), \quad (8)$$

where: v_i^{k+1} – velocity of particle i at iteration $k+1$; w – weighting function; c_j – weighting factor; *rand* – random number between 1 and 0; s_i^k – current position of particle i at iteration k; $pbest_i$ – *pbest* of the particle i; *gbest* – *gbest* of the group.

The weight function, which is usually used in equation (9), is written as follows [8–22]:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{k_{\max}} \times k, \quad (9)$$

where: $w_{\max}$ – initial weigh; $w_{\min}$ – final weigh. While referring to equation (9), a certain speed, gradually approaching *pbest* and *gbest*, can be calculated. The current position S_i^k, which represents the research of the point within solution space, can be modified by the following equation:

$$s_i^{k+1} = S_i^k + v_i^{k+1}. \quad (10)$$

The application, detail and implementation of the PSO for OVD in electrical power systems considering minimization total active power losses are presented in [9–12].

5. HYBRID METHOD FOR OVD

The hybrid method integrating the PSO and the IPM can be divided in two parts. The first part employs the IPM to solve the OVD problem approximated as a continuous problem. Then the optimal solution obtained is rounded off, in which for discrete variables are used as the initial agent of PSO algorithm. The second part is to combine the PSO algorithm with the IPM to solve the OVD for the final optimal solution. The procedure of the proposed hybrid method is summarized as follows:

Step 1. Solve the OVD problem by IPM with relaxing the discrete variables to obtain the initial solution $[V_G^0, V_{SVC}^0, Q_C^0, t^0]$.

Step 2. Set iteration count $k = 1$.

Step 3. Determine the optimal Q_C^k, t^k by solving the discrete optimization sub-problem using PSO algorithm with keeping $V_G^k = V_G^{k-1}$ and $V_{SVC}^k = V_{SVC}^{k-1}$. And evaluated of the objective function (total active power losses) by load flow.

Step 4. Determine the optimal V_G^k, V_{SVC}^k by solving the continuous optimization sub-problem using IPM with the values of Q_C^k, t^k obtained in step 3 constant. In the same way, the solution of PSO is used as starting point of IPM.

Step 5. If convergence criterion is satisfied, terminate the calculation. If not, set $k = k + 1$ and then step 3.

6. NUMERICAL SIMULATION AND RESULTS

The one-line diagram of the western Algerian 220/60 kV transmission / subtransmission system is shown in Fig. 1. The Algerian network is characterized by long transmission lines, an uneven distribution of reactive power reserves among available generators, as well as an insufficient number of shunt capacitors. As a consequence, operators are routinely facing severe voltage problem (violation), and the reactive power dispatch has become one of the most relevant concerns in the control center for the western Algerian transmission system. This problem is resolved by Khiat [2]. Actually this network is modified with regard to the network quoted in [2–11]. Its main data and operational limits are summarized in Table 1 and Table 2.

For the considered power system, tree cases are studied.

Case 1: Base case (load flow).

Case 2: Results of the IPM, considering continuous variables $[V_G, V_{SVC}]$ and fixed discrete variables $[Q_C, t]$.

Case 3: Results of the proposed hybrid method.

Case 4: Results of the IPM, considering both continuous and discrete variables $[V_G, V_{SVC}, Q_C, t]$.

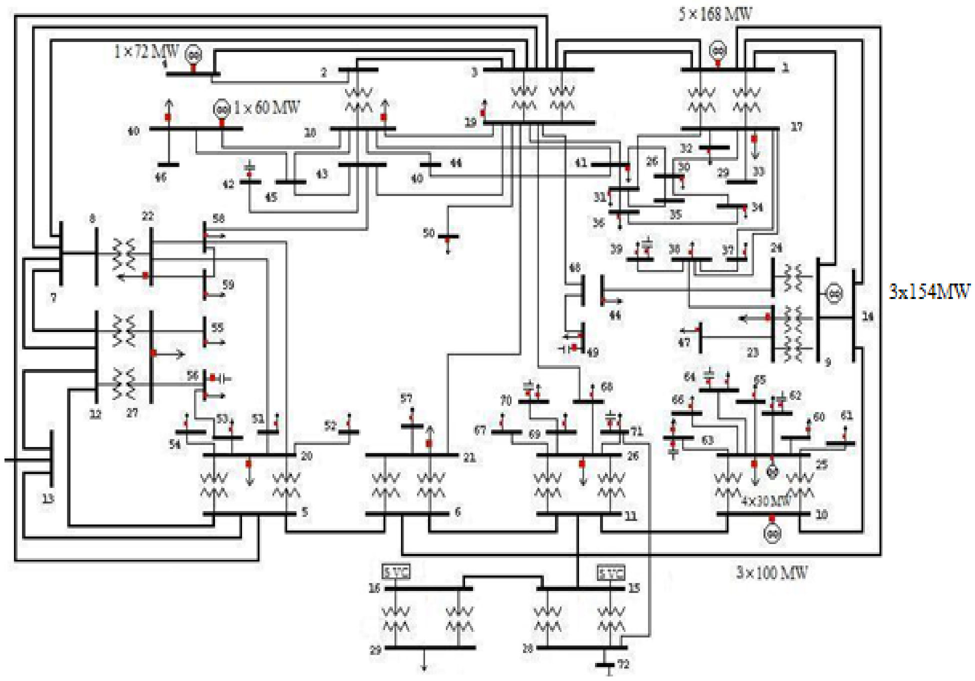

Fig. 1 – Western Algerian 220/60 kV transmission/sub-transmission system by M. Khiat.

Table 1
Main data of the western Algerian system

Parameter	Values
Load buses	66
Generator buses	6
Lines	86
Transformer taps	13
Shunt capacitors	9
Shunt SVC	2
Active load demand	1255.5 MW
Total active losses	53.2 MW

Table 2
Limits of variables and bus voltages

Magnitudes	Lower	Upper
V1...V13[p.u.]	0.99	1.11
V13..V72[p.u.]	0.95	1.10
t1 …t13 [p.u.]	0.90	1.10
QG1 [Mvar]	–100.0	400.0
QG4 [Mvar]	–25.0	30.0
QG9 [Mvar]	–60.0	250.0
QG10[Mvar]	–50.0	200.0
QG25[Mvar]	–50.0	80.0
QG40[Mvar]	–20.0	36.0
QCap[Mvar]	0.0	10.0
QSVC[Mvar]	–10.0	40.0

The obtained results are drawn up in Tables 3, 4, 5, 6, 7 and 8.

Table 3

Shunt capacitors in [Mvar]

Bus	Case 1	Case 2	Case 3	Case 4
39	10	10	10	10
42	5	5	10	10
49	10	10	10	10
56	10	10	10	10
62	5	5	4.5	4.54
63	10	10	10	10
64	10	10	7.4	7.39
70	10	10	10	10
71	5	5	7.3	7.24

Table 5

Reactive power of generators in [Mvar]

Bus	Case 1	Case 2	Case 3	Case 4
1	358.88	352.90	339.76	342.71
4	22.98	30.00	30.00	30.00
9	36.83	13.13	6.34	–2.73
10	25.20	52.69	–9.24	–10.40
25	–27.45	–37.97	29.95	34.73
40	24.38	36.00	36.00	36.00

Table 4

Shunt SVC in [Mvar]

Bus	Case 1	Case 2	Case 3	Case 4
15	18.10	17.89	14.14	8.66
16	14.59	8.18	8.15	8.53

Table 6

Transformer tap ratios in [p.u]

Branch number	Case 1	Case 2	Case 3	Case 4
1-17	0.980	0.980	0.920	0.930
2-18	0.990	0.990	1.000	0.916
3-19	0.980	0.980	0.990	0.942
5-20	0.980	0.980	0.950	0.919
6-21	0.980	0.980	1.010	0.956
8-22	0.990	0.990	0.940	0.912
9-23	0.940	0.940	0.940	0.942
9-24	0.990	0.990	0.980	0.985
10-25	0.960	0.960	1.000	1.000
11-26	0.950	0.950	0.950	0.949
12-27	0.980	0.980	0.900	0.900
15-28	1.000	1.000	0.980	0.967
16-29	1.000	1.000	0.960	0.946

Table 7

Voltages generators; shunt SVC and capacitors in [p.u]

Bus voltages	Case 1	Case 2	Case 3	Case 4
VG1	1.1000	1.1000	1.0972	1.0967
VG4	1.0600	1.0653	1.0709	1.0594
VG9	1.1000	1.0921	1.0912	1.0907
VG10	1.0900	1.0960	1.0989	1.1000
VG25	1.1000	1.1000	1.1000	1.1000
VG40	1.0000	1.0121	1.0270	1.0858
VSVC15	1.1000	1.0867	1.0841	1.0723
VSVC16	1.1000	1.0689	1.0663	1.0539
VC39	0.9508	0.9500	1.0038	1.0040
VC42	0.9658	0.9773	1.0053	1.0646
VC49	0.9699	0.9668	0.9702	0.9945
VC56	0.9682	0.9705	1.0455	1.0611
VC62	1.0929	1.0929	1.0916	1.0916
VC63	0.9946	0.9946	0.9946	0.9946
VC64	1.0919	1.0918	1.0779	1.0779
VC70	0.9630	0.9622	0.9703	0.9704
VC71	1.0788	1.0676	1.0927	1.0948

Table 8

Total active power loss

	Case 1	Case 2	Case 3	Case 4
Losses [MW]	53.2	52.70	50.5	49.7
Reduction[MW]		0.50	2.70	3.50
Reduction[%]		0.94	5.07	6.58

To improve the results in this paper the hybrid method is applied. Several simulations were performed to assess on the voltages and the total active power losses.

The obtained results in the cases 4 were better than for case 3 concerning active power losses, this is that all the variables, discrete and continuous in the case 4 are considered as variables of control, on the other hand in the case 3 the results are closer to the reality.

As a conclusion, it is interesting to optimize the continuous and discrete variables, the voltage of generators, and SVC by IPM and transformer tap ratios and shunt capacitors by PSO method.

Finally, a comparison between case 1 and case 3, shows that this operation optimization also results in a decrease of the total active power losses from 53.2 to 50.5 MW (5.07%).

7. **CONCLUSION**

The minimization of total active power transmission losses by an hybrid method based on PSO algorithm and IPM has been proposed in this paper. The problem formulation has been addressed in detail and several implementation issues have been discussed. The PSO algorithm is very powerful for dealing with discrete variables, while the IPM is attractive for the efficiency of dealing with the large-scale continuous nonlinear programming. The hybrid method combines the advantages of PSO method and IPM. Simulation and results of applying a prototype version to the Algerian transmission/sub-transmission network are depicted showing that the proposed hybrid algorithm is very efficient.

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