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Optimal Power Flow Using Particle Swarm Optimization

[1]T. Saravanan, [2]G. Saritha and [1]V. Srinivasan

[1]Department of ETC, Bharath University, Chennai, India
[2]Sathyabama University, Chennai, India

Abstract: This paper proposes the application of Particle Swarm Optimization (PSO) technique to solve Optimal Power Flow with inequality constraints on Line Flow. To ensure secured operation of power system, it is necessary to keep the line flow within the prescribed MVA limit so that the system operates in normal state. The problem involves non-linear objective function and constraints. Therefore, the population based method like PSO is more suitable than the conventional Linear Programming methods. This approach is applied to a six bus three unit system and the results are compared with results of Linear Programming method for different test cases. The obtained solution proves that the proposed technique is efficient and accurate.

Key words: Security Constrained Economic Dispatch % Optimal Power Flow % Particle Swarm Optimization

INTRODUCTION

Optimal Power Flow is a very large and very difficult mathematical problem which calculates the optimum generation schedule and other control variables to achieve the minimum cost or minimum loss together with meeting engineering and power balance constraints. In the operation of power system, at any time, if any of the transmission line is overloaded, that line has to be brought out of service. Therefore, to operate the system in a secured manner, the limits on line flows should also be included in the Optimal Power Flow problem.

OPF problem with engineering constraints, power balance equality constraints and line flow inequality constraints is a complicated nonlinear optimization problem. Various optimization techniques like, (i) Gradient Method (ii) Newton Method (iii) Linear Programming (iv) Recursive Quadratic Programming (v) Continuation Methods have been proposed to solve this kind of Security Constrained Economic Dispatch (SCED) problem in the past years [1].

The Gradient and Newton methods of solving OPF suffer from the difficulty in handling inequality constraints. In Linear Programming approach, the convex cost curve is approximated as a series of straight line segments and the set of power balance constraints are formulated by DC power flow assuming that the change in voltage angle is not significant during normal operating conditions. The papers [1] to [4] deal with Linear Programming technique and its various formulations such as Interior Point method, Primal Dual method, Predictor Corrector Approach. The non-linear decomposition method is applied in [5] which utilize AC or DC power flow. Recently, the OPF with security constraints is modeled for deregulated environment [6].

Now days, the advancements in computing and parallel processing enables the population based search procedures like Genetic Algorithm, Evolutionary Programming and Particle Swarm Optimization [7] to apply in the real time applications [8, 9] like OPF. In this paper, the Particle Swarm Optimization method is applied to solve Optimal Power Flow. The effectiveness of the proposed method is proved by applying it for a six-bus three-unit system.

Overview of Particle Swarm Optimization: The PSO is based on the r esearches on social behavior of organisms such as fish schooling and bird- flocking. PSO provides a population-based search procedure in which individuals called particles change their positions (states) with time. While flying in a multidimensional search space, each particle adjusts its position with the new velocity which depends on its own experience (pbest) and the experience of neighboring particles (gbest), i.e making use of the best position encountered by itself and its neighbors [10].

Corresponding Author: T. Saravanan, Department of ETC, Bharath University, Chennai, India.

Let x and v denote a particle coordinates (position) and its corresponding flight speed (velocity) in a search space, respectively.

The i^{th} particle is represented by, $x_i = (x_{i1}, x_{i2}, \ldots x_{id})$ in the d-dimensional space.

The best previous position of the i^{th} particle is $pbest_i = (pbest_{i1}, pbest_{i2}, \ldots, pbest_{id})$

The index of the best particle among all particles in the group is represented by the *gbest*. The rate of the velocity for particle 'i' is represented as:

$v_i = (v_{i1}, v_{i2}, \ldots, v_{id})$.

The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest_{ij}$ and $gbest_i$ as shown in the following formulae:

$$v_{ij}(t+1) = w(t)^* v_{ij}(t) + c_1{}^* rand\,(\,)^*(pbest_{ij} - x_{ij}(t)) + c_2{}^* Rand\,(\,)^*(gbest_j - x_{ij}(t)) \quad (1)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (2)$$

$i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, d$

where,

n - Number of particles in a population (Population size) d - Number of variables in a particle
t - Iteration count
w - Inertia weight factor
c_1, c_2 - Acceleration constants

rand ( ), Rand() -Uniform random value in the range [0, 1];
$v_i(t)$ - Current velocity of i th particle at t th iteration,
vj min vij (t) vj max
$x_i(t)$ - Current position of i^{th} particle at t^{th} iteration.

In the above procedure, if the parameter v_{max} is too high, particles might fly past good solution. If v_{max} is too small, particles may not explore sufficiently beyond local solutions.

The constants c_1 and c_2 represent the weighting of the stochastic acceleration terms that pull each particle toward the pbest and gbest positions. Suitable selection of inertia weight w in (3) provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution, the inertia weight w is set according to the following equation:

$$w(t) = w_{max} - \{(w_{max} - w_{min}) / t_{max}\}^* t \quad (3)$$

where t_{max} is the maximum number of iterations (generations) and 't' is the current number of iterations.

Problem Formulation: In the Optimal Power Flow with Line Flow Constraints, minimization of either the cost of generation or real power loss may be considered as objective function 'f'. The control variable 'u' may be taken as either a vector of real power generated or the generation voltage or both depends on the requirement. Mathematically, it can be formulated as,

Min f(x,u) (4)
subject to
g(x) = 0 (5)
$Pg_{min}(i)$ Pg(i) $Pg_{max}(i)$ (6)
$U_{min}(i)$ U(i) $U_{max}(i)$ (7)
S(i,j) S_{max} (i,j) (8)

The equations (5) to (8) represents the constraints on the power balance, maximum generation limit, system voltage limits and line flow limits respectively.

Algorithm:

Step 1: In OPF problem, each i^{th} particle is represented by $x_i = (x_{i1}, x_{i2}, \ldots x_{id})$

where 'x' consists of set of control variables 'u', Real power generation or voltage or both of all the units.

Initialize randomly the individuals (particles) of initial population (the size of population matrix is nXd) and velocities according to limits of each variable [11].

Step 2: To each individual x_i of the population, run the load flow program to find the system voltages of dependent and controlled buses, real and reactive power generation of slack bus and controlled buses, MVA flows of transmission lines and total real power loss. The execution of load flow ensures to satisfy the constraint (5). Here, in this paper, full Newton method is used for its accuracy.

Step3: For all the individuals, calculate the objective function value 'f' that may be the total cost of generation or the total real power loss. For any individual, if any of the constraints specified by (6) to (8) is violated, add penalty to its objective function.

Step 4: Each initial searching point is assigned as pbest of the individual and the best evaluated value among pbest's is set as gbest [12].

Step 5: Modify the velocity of each individual x_i according to (1). If any new velocity exceeds its limit set it at the limit.

Step 6: Modify the position of each individual according to (2). The modified values must satisfy the constraints on their limits.

Step 7: Find the objective function for the new position in the same way as initial positions (Steps 2& 3).

Step 8: Compare each individual's objective function value with its pbest and if the objective function of the new position is less than previous pbest, assign the present position as pbest. The best evaluated value among pbest's is denoted as gbest.

Step 9: Repeat the step numbers 5 to 8 until the number of iterations reaches the maximum.

Step 10: The latest value of gbest is the optimum solution that minimizes the objective function.

RESULTS

The proposed algorithm is implemented on a six-bus three-unit system and the results are compared with Linear Programming method described in [10]. Table 1,2,3 provides line, bus, generator data of the system under consideration respectively. The solution for the problem is divided into three different cases. Case(i) deals with the minimization of generation cost by controlling generation schedule alone. Case (ii) minimizes the generation cost by choosing generation schedule and generator voltages as control variable. Case(iii) deals with minimization of losses by considering generator voltages as control variables.

Case (I): In this case the power outputs of three generators are considered as the control variable and OPF is executed to minimize the operating cost given by

n
$f(u) = a_i P_{gi}^2 + b_i P_{gi} + c_i$ (9) i=1
and $u = [P_{g1}\ P_{g2}\ \dots P_{gn}]$

The Table 4 depicts the effectiveness of the proposed approach as compared to the Linear Programming Method. It is observed that the optimum generation schedule results into significant reduction of real power loss and the operating cost. Here, the reactive generation of bus 3 is at its maximum both in LP method as well as in the proposed method. The dependent bus voltages are constrained to vary within ±5%.

Table 5 shows the line flow on the various lines in both the directions obtained from PSO method and their MVA limits. It is observed that line2-4 is at its maximum MVA limit and the losses incurred are also high in the line. While solving using LP method the same line is found to impose binding constraint. From the table it is clear that line flow in all other lines lie well below the limit.

Case(II): In this case, the power outputs of three generators and its voltages are considered as the control variable and OPF is executed to minimize the operating cost (9) with the following six control variables.

$u = [P_{g1}\ P_{g2} \dots P_{gn}\ |U_1|\ |U_2| \dots |U_n|]$

From Table 6, it is clear that choosing generator voltages as additional control variable results in reduction of real power losses and also the overall operating cost as compared to Case(i). Comparison of results in Table 6 and 7 provides valuable information on the advantage of using secondary voltage control loop in addition to the governor control [13]. In LP method, line flow limit constraint on line 2-4 is found to be binding and so it is found to yield better solution than the proposed method. In PSO the line flows are well below the limits for all the lines as shown in Table 7.

Table 8 shows the line flows for case(ii) obtained from PSO method and their MVA limits. Here, the reactive generation of bus 3 is at its maximum both in LP method as well as in the proposed method.

Case (III): In this case the generator voltages of three units are considered as the control variable and OPF is executed to minimize the transmission losses in the systems as given by:

$$\text{Min } P_{loss}(x) \Rightarrow \text{Min } P_{slack}(x) \quad (10)$$
and $u = [|U_1|\ |U_2| \dots |U_n|]$;

As the control variables are only generator voltages and not generator powers, any variations in the system losses will directly reflect in slack bus generation. Therefore, in (10) the minimization of real power loss is modeled as minimization of slack bus power. The Table 8 and 9 illustrates the effectiveness of the proposed approach. It is observed that the optimum voltage schedule yields reduction of real power loss [14].

Table 1: Line Data for Test System

From bux	To bux	R (pu)	X (pu) Admittance	Shunt (pu)	Line Flow limits (MVA)
1	2	0.10	0.20	0.02	40
1	4	0.05	0.20	0.02	60
1	5	0.08	0.30	0.03	40
2	3	0.05	0.25	0.03	40
2	4	0.05	0.10	0.01	60
2	5	0.1	0.30	0.02	30
2	6	0.07	0.20	0.025	90
3	5	0.12	0.26	0.025	70
3	6	0.02	0.10	0.01	80
4	5	0.20	0.40	0.04	20
5	6	0.10	0.30	0.03	40

Table 2: Bus Data

Bus Number	Voltage (pu)	Pgen (pu MW)	Pload (pu MW)	Qload (pu MVAR)
1	1.05	-	-	-
2	1.05	0.50	0.0	0.0
3	1.07	0.60	0.0	0.0
4			0.7	0.7
5			0.7	0.7
6			0.7	0.7

Table 3: Generator Data

Gen No	a (Rs /MW^2hr)	b (Rs/MWhr)	c (Rs/hr)	Pgmin (MW)	Pgmax (MW)	Qgmax (MVAR)
1	0.00533	11.669	213.1	50.0	200	-
2	0.00889	10.333	200.0	37.5	150	70
3	0.00741	10.833	240.0	45.0	180	70

Table 4: Solution of Test System under Case(I)

Method	Pg1 (MW)	Pg2 (MW)	Pg3 (MW)	$_{\|v1\|}$sched	$_{\|v2\|}$sched	$_{\|v3\|}$sched	Loss (MW)	Cost (Rs/hr)
Base case	107.9	50	60	1.5	1.0499	1.0429	7.87	3189.4
LP	86.9	59.3	71.0	1.05	1.05	1.0458	7.14	3157.9
PSO	78.98	65.92	72.0	1.05	1.05	1.0644	6.909	3146.2

Table 5: Line Flows of System Using Pso under Case(I)

Line		Line flow i-j (MVA)		Line flow j-i (MVA)			
From	To	Si-j	$\|S_{j-i}\|$	Sj-i	$\|S_{j-i}\|$	P_{loss} (MW)	MVA limit
1	2	16.30-9.98i	19.11	-16.00+6.16i	17.15	0.2959	40
1	4	34.56+22.51i	41.25	-33.74-23.39i	41.06	0.8188	60
1	5	22.11+13.5i	31.19	-27.33-16.7i 32.08	0.7791	40	
2	3	-0.78-9.21i	9.24	0.80+2.58i	2.70	0.0161	40
2	4	41.16+43.64i	59.99	-39.48-42.37i	57.91	1.6767	60
2	5	17.04+15.79i	23.24	-16.49-18.26i	24.6	0.5576	30
2	6	24.5+14.69i	28.57	-23.92-18.31i	30.13	0.5745	90
3	5	23.14+20.08j	30.64	-22.02-22.9i	31.77	1.1238	70
3	6	48.05+57.35i	74.82	-47.04-54.43i	71.94	1.0115	80
4	5	3.23-4.23i	5.32	-3.21-3.48i	4.74	0.0217	20
5	6	-0.936-8.549i	8.6	0.97+2.74i	2.91	0.034	40

Table 6: Solution of Test System under Case(II)

Method	Pg1 (MW)	Pg2 (MW)	Pg3 (MW)	$_{\|U1\|}$sched	$_{\|U2\|}$sched	$_{\|U3\|}$sched	Loss (MW)	Cost (Rs/hr)
LP	52.23	87.5	77.0	1.05	1.0429	1.0499	6.73	3127.4
PSO	54.60	85.11	77.15	1.05	1.0317	1.0496	6.87	3129.9

Table 7: Line Flows of System Using Pso under Case(II)

Line		Line flow i-j (MVA)		Line flow j-i (MVA)			
From	To	Si-j	$\lvert S_{j-i} \rvert$	Sj-i	$\lvert S_{j-i} \rvert$	P_{loss} (MW)	MVA limit
1	2	6.02+4.38i	7.45	-5.95-8.57i	10.43	0.0007	40
1	4	26.56+31.62i	41.30	-25.72-32.37i	41.35	0.0084	60
1	5	22.01+19.62i	29.49	-21.28-22.99i	31.33	0.0073	40
2	3	-1.26-10.31i	10.39	1.288+3.94i	4.14	0.0002	40
2	4	48.63+35.13i	59.99	-46.9-33.69i	57.75	0.0173	60
2	5	19.13+13.43i	23.37	-18.56-15.73i	24.33	0.0057	30
2	6	24.56+13.39i	27.82	-23.9-16.86i	29.33	0.0057	90
3	5	25.92+18.25i	31.69	-24.7-20.72i	32.24	0.0121	70
3	6	49.95+57.82i	76.4	-48.87-54.47j	73.17	0.0108	80
4	5	2.63-3.94i	4.73	-2.62-3.58i	4.43	0.0001	20
5	6	-2.84-6.98i	7.53	2.86+1.34j	3.16	0.0003	40

Table 8: Solution of Test System under Case(III)

Method	Pg1 (MW)	Pg2 (MW)	Pg3 (MW)	$\lvert U_1 \rvert$sched	$\lvert U_2 \rvert$sched	$\lvert U_3 \rvert$sched	Cost (Rs/hr)	Loss (MW)
LP	107.743	50	60	1.05	1.0429	1.0499	3187.8	7.7436
PSO	107.712	50	60	1.05	1.0346	1.0436	3187.4	7.7129

Table 9: Line Flows of Test System Using Pso under Case(III)

Line		Line flow i-j (MVA)		Line flow j-i (MVA)			
From	To	Si-j	|Sj-i|	Sj-i	|Sj-i|	P_{loss} (MW)	MVA limit
1	2	29.01-7.69i	30.02	-28.22+4.93i	28.65	0.0079	40
1	4	43.35+26.35i	50.72	-42.12-25.57i	49.28	0.0122	60
1	5	35.36+17.13i	39.28	-34.15-18.71i	38.94	0.0121	40
2	3	2.43-7.41i	7.79	-2.42+0.98i	2.61	0.0001	40
2	4	33.49+41.42i	53.26	-32.12-40.71i	51.86	0.0137	60
2	5	15.86+15.53i	22.19	-15.33-17.97i	23.62	0.0053	30
2	6	26.44+15.42i	30.81	-25.76-19.05i	32.04	0.0068	90
3	5	18.65+18.92i	26.57	-17.75-22.05i	28.30	0.0090	70
3	6	43.77+55.46i	70.65	-42.84-52.81i	68.00	0.0094	80
4	5	4.25-3.72i	5.64	-4.21-3.78i	5.66	0.0004	20
5	6	1.429-7.492i	7.63	-1.40+1.87i	2.33	0.0003	40

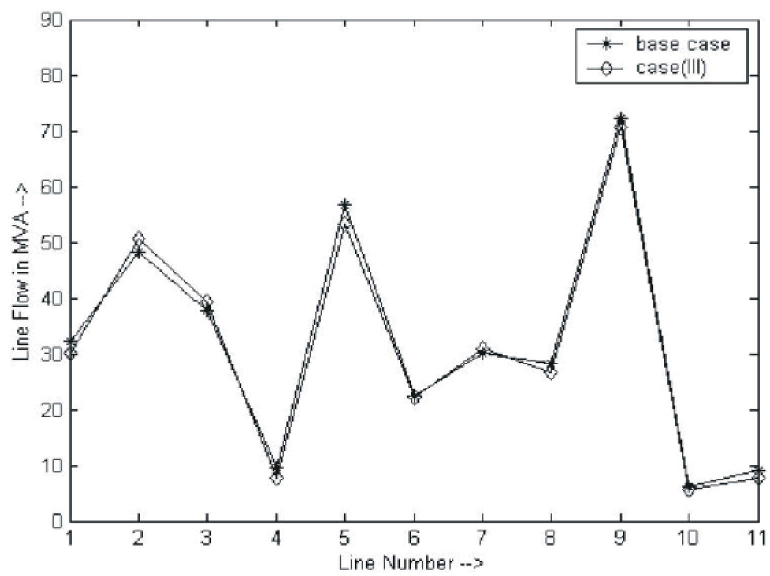

Fig. 1: Comparison of line flows in Base case& PSO for test Case(III)

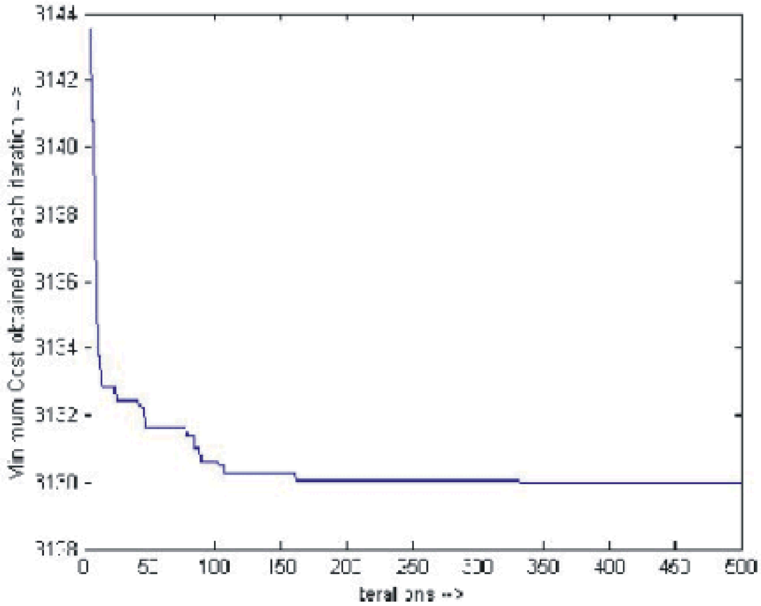

Fig. 2: Convergence Characteristic of PSO for test Case(III)

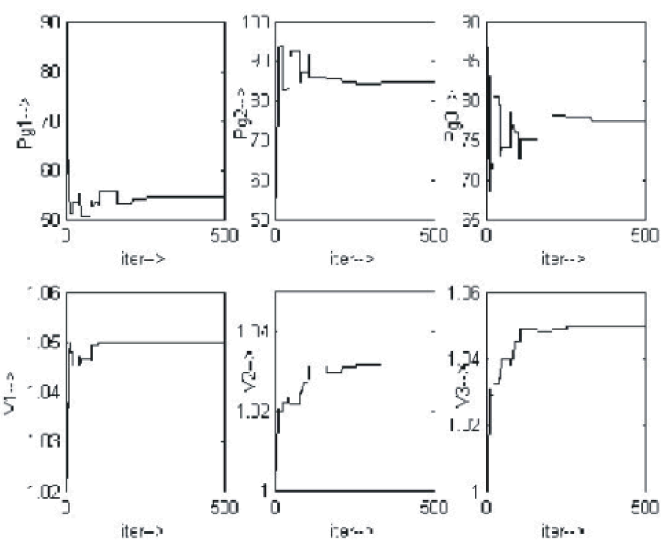

Fig. 3: Convergence of Control variables for test CaseII

The Line flows in this case are compared with the base case line flows in Fig. 1. From Fig. 1 it is concluded that line flows are well controlled if the voltage generating units are controlled for minimizing losses.

Parameter Selection: For the test system considered, the following PSO parameters are chosen after a trial and error process.

v_{max}=10%of 'x' ; v_{min}=0; w_{max}=0.9; w_{min}=0.2; c_1=5; c_2=5; Population size=10;

Maximum number of Generations is found to be 100 for case (I) and (III) where there are only three control variables and it is 500 for test case(II) where the number of control variables are increased to 6.

The acceleration constants 'c1' and 'c2' are varied in unison from 2 to 8. It is observed that too low value of acceleration (c_1=c_2=2) results in slow rate of convergence and the global optimum may not be reached within the specified maximum number of generations. On the other hand, high value of acceleration constants (c_1=c_2 =8) has high rate of convergence at start but there is a chance of sticking on at the local optimum solution i.e., never converging to global solution. In this paper acceleration constants are chosen to be 5 as optimum. The convergence characteristic of PSO is shown in Fig. 2 for the test case (ii) with the above specified PSO parameters [15-17].

Fig. 2 shows the convergence of control variables for the test case (ii). The figure reveals that the control variables are also converged while the objective function is minimized.

CONCLUSION

Now days, as restructuring of power system increases the congestion of power flow in the transmission system, the Optimal Power Flow plays an important role in day to day power system operation and control to maintain system security. Particle Swarm Optimization technique is found to be highly suitable for Optimal Power Flow problem with line flow constraints. It is also assured that the algorithm would function in the same way for large power systems with more number of lines and generating units. The computational results of the sample system reveal that the proposed method is much more efficient and versatile than other methods described.

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