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Optimal Power Flow Solution Using Particle Swarm Optimization

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ABSTRACT
In this paper Particle swarm optimization (PSO) algorithm has been applied to solve Optimal Power Flow (OPF) problem (OPFP). The proposed work has been examined and tested on IEEE-9 bus system with six different objectives based onfuel cost, Transmission losses and Voltage profile improvement. The results drawn show its validity and effectiveness.
Keywords: Economic Load dispatch (ELD), Optimal power flow (OPF), Particle swarm optimization (PSO)

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I. INTRODUCTION

Optimal power flow (OPF) has become one of the most important problems for the optimal operation of modern power system. In past two decades OPF has received much attention. The main function of electric power system is to optimizeobjectives such as fuel cost, voltage improvement and transmission losses by optimal adjustments of the control variables while satisfying the equality and inequality constraints [1-2]. The equality constraints are the power balance equations and inequality constraints are the operating limits of control variables such as generator real generations and voltage at generators.
A number of optimization techniques have been applied to solve OPFP [3-9] such as quadratic programming [3], nonlinear programming [4-5], linear programming [6-7], newton based techniques [8] and interior point methods [9] etc. Generally quadratic programming based algorithms have drawback of piecewise quadratic cost approximation, nonlinear programming based approaches have drawback of insecure convergence, newton based techniques fails to converge due to inappropriate initial conditions, linear based algorithms are fast but have disadvantage of piecewise liner cost approximation and interior point methods are efficient but if step size was not chosen properly then sub linear problem have infeasible solution. OPF is highly nonlinear multimodal problem there exist more than one local optimal solution so hence local optimal techniques are not suitable for such problems. Considering these problems heuristic techniques such as such as genetic algorithm [10], Particle swarm optimization [11], Differential Evolution (DE) [12], Simulating Annealing (SA) [13], Evolutionary Programming (EP) [14] and biogeography based optimization (BBO) [15] has been applied by researchers to solve OPFP.In this paper PSO algorithm has been applied to solve the OPFP. The developed algorithm based on PSO has been applied on IEEE 9 bus system. Six different cases related to fuel cost, voltage deviation and transmission losses have been investigated. The results obtainedshows validation and effectiveness of PSO algorithm.

II. PROBLEM FORMULATION

2.1. Problem Objectives

The main objective of this problem is to minimise the total fuel cost, Voltage deviation and Transmission losses with respect equality and in equality constraints. The details of objectives are given as below.

2.1.1. Minimization of fuel cost considering AP generation.

The fuel cost function considering AP generation by each thermal generator is given by a quadratic function can be written as [2]:

$$F_1(P_{gi}) = \sum_{i=1}^{NG}\left(a_i P_{gi}^2 + b_i P_{gi} + c_i\right)\$/\text{hr.} \quad (1)$$

where, a_i, b_i and c_i are the fuel cost coefficients of i[th] unit , P_{gi} is active power generation at i[th] generator bus andNG is the number of generators.

2.1.2. Minimization of transmission Losses

The losses in transmission lines are given by following equations

$$F_2 = \sum_{i=i}^{NB}\sum_{\substack{j=1 \\ j\notin i}}^{NB} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) \quad (2)$$

Where $|V_i|\angle\delta_i$: Voltage phasor in bus *i*

$Y_{ij}\angle\theta_{ij}$: ijth elements of admittance matrix

2.1.3. Voltage Deviation

The voltage profile is the most important index for system service quality. The improvement of the voltage profile contains reducing the deviation of load bus voltage from the unity. Considering the cost-based objectives in the OPF problem may result in a feasible solution that has unattractive voltage profile, so it is important to improve the voltage profile by minimizing the load bus voltage deviation from 1.0 per unit. The voltage deviation is represented by following function.

$$F_3 = \sum_{i=1}^{N_L}|v_i - 1| \quad (3)$$

2.2. Constraints

2.2.1. AP and RP balance constraints

Total AP generation must meet the AP demand and the AP losses [28].

$$\sum_{i=1}^{NG}(P_{gi}) - (\sum_{i=1}^{NB} P_{Di} + P_L) = 0 \quad (4)$$

where, P_D is the AP demand and P_L is the AP losses.

Total RP generation must meet the RP demand and the RP losses [28].

$$\sum_{i=1}^{NG}(Q_{gi}) - (\sum_{i=1}^{NB} Q_{Di} + Q_L) = 0 \quad (5)$$

where, Q_D and Q_L are the Reactive power demand and reactive power losses and are given as:

$$P_L = \sum_{i=i}^{NB}\sum_{\substack{j=1 \\ j\notin i}}^{NB} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) \quad (6)$$

$$Q_L = \sum_{i=i}^{NB}\sum_{\substack{j=1 \\ j\notin i}}^{NB} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i) \quad (7)$$

Operating limits.

The AP and RP generation by each unit must lie between minimum and maximum values.

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad (i=1,2,......, NG) \quad (8)$$

where, $P_{gi}^{\min}$ and $P_{gi}^{\max}$ are the minimum limit and maximum limit for AP generation by i[th]unit.

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} (i=1,2,......, NG) \quad (9)$$

where, $Q_{gi}^{\min}$ and $Q_{gi}^{\max}$ are the minimum limit and maximum limit for RP power generation.

The voltage at each bus must be in the minimum limit and maximum limit

$$|V_i^{\min}| \le |V_i| \le |V_i^{\max}| \quad (i=1,2,......, NB)$$

(10)

III. PARTICLE SWARM OPTIMIZATION(PSO)

Let X and v denotes a particle's coordinate (position) and its corresponding velocity in a search space, respectively. Therefore, the *ith* particle is represented as $X_i = [X_{i1}, X_{i2}, X_{i3},........,X_{iNG}]$ in the NP-dimensional space. The best previous position of each particle is recorded and represented as $Xb_i= [Xb_{i1}, Xb_{i2}, Xb_{i3}... Xb_{iNG}]$. The index of best particle among all the particles in the group is represented by the $[G_1, G_2, G_3,......., G_{NG}]$. The rate of velocity of the particle is represented as $v_i=[v_{i1}, v_{i2}, v_{i3},.........., v_{iNP}]$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from Xb_{ij} to G_j as shown in following formulas.

$$v_{ij}^{r+1} = W \times v_{ij}^{r} + C_1 \times R_1 \times (Xb_{ij}^{r} - X_{ij}^{r}) + C_2 \times R_2 \times (G_j^{r} - X_{ij}^{r}) \;\; (i = 1,2,....NP;\ j = 1,2....,NG) \quad (11)$$

$$X_{ij}^{r+1} = X_{ij}^{r} + v_{ij}^{r+1} (i = 1,2,.....NP;\ j = 1,2.....,NG) \quad (12)$$

where, NP is the number of particles in a group, NG is the number of members in a particle, r is the pointer of iteration (generation), W is the inertia weight factor, C_1 and C_2 are the acceleration constants, R_1 and R_2 are uniform random values in range[0,1], v_{ij}^{r} is the velocity of jth member of ith particle at rth iteration, $v_j^{min} \le v_{ij}^{r} \le v_j^{max}$, P_{ij}^{r} is the current position of j^{th}member of i^{th} particle at the r^{th} iteration.

In the above procedure, the parameter $v_j^{\min}$determined the resolution, or fitness, with which regions are to be searched between the present position and the target position. If $v_j^{\max}$is too high, particles might fly past good solutions. If $v_j^{\max}$is too small, particle may not explore sufficiently beyond local solutions. In many experiences with PSO, $v_j^{\max}$was often set at 10-20% of the dynamic range of the variable on the variable of each dimension

The constant C_1 and C_2 represents the weighting of the stochastic acceleration terms that pull each particle toward the Xb_{ij}^{r}, G_j^{r} positions. Low values allow particles to roam far from the target region before being tugged back. On the other hand, high values result in abrupt movement toward, or past, target regions. Hence, the acceleration constants C_1 and C_2 were often set to be 2.0 according to past experiences **.**

The generalised Eq.(11) can be updated in order to find new value of velocity by considering the global best and particle best position as given below.

$$v_{ij}^{new} = W \times v_{ij} + C_1 \times R_1 \times (X_{ij}^{best} - X_{ij}) + \left(C_2 \times R_2 \times (G_j^{best} - X_{ij})\right) \quad (13)$$

Now the new positions are updated using Eq.(13) as given below.

$$X_{ij}^{new} = X_{ij} + v_{ij}^{new} (i = 1, 2 ...NP;\ j = 1,2....NG) \quad (14)$$

In the strategy of PSO, the particle's best position, x_{ij}^{best} and the global best position G_j^{best} are the key factors. The best position out of all x_{ij}^{best} is taken as G_j^{best} Suitable selection of inertia weight in Eq.(15) provides balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. As originally developed, W often decrease linearly about 0.9 to 0.4 during a run. In general inertia weight W is set according to the following equation**.**[2],[11],[16-17].

$$W = W^{\max} - \frac{W^{\max} - W^{\min}}{IT^{\max}} \times IT \quad (15)$$

where, $IT^{\max}$ is the maximum number of iterations (generation) and IT is the current number of iterations

IV. ALGORITHM FOR SOLUTION TECHNIQUE

According to the discussion in above sections, the following procedure can be used for implementing the PSO algorithm.

- For each particle in the swarm X_i
- Initialize the particle's position with a uniformly distributed random vector in the lower and upper boundaries of search-space.
- Apply Load flow and calculate the values of Transmission losses and Voltage deviation.
- Evaluate the performance (fitness) of each particle using Equation
- Find the minimum fitness out of each particle performance
- Assign the particle's best known position(local) to its initial position

- Assign the Global best position to the swarm's best known position(local) according to the minimum fitness value
- Initialize the particle's velocity within minimum and maximum boundaries of search-space
- Until a termination criterion is met (e.g. number of iterations performed, or adequate fitness reached), repeat
- For each particle
- Create a uniformly distributed random vectors R_1 and R_2
- Update the particle's velocity: using
- Update the particle's position by adding the velocity:
- Apply Load flow and calculate the values of Transmission losses and Voltage deviation according to new positions.
- Evaluate the performance(fitness)using according to new positions:
- IF the new fitness is less than the previous fitness THEN
- Update the new particle positions as the particle's best(local) known position
- Assign new fitness as the local fitness and find the minimum out of each.
- Update the swarm's best (global best) known position according to minimum fitness.

Now best new positions hold the best found solution.

V. RESULTS AND DISCUSSION

This section represents the results obtained from the proposed algorithms. The problem was solved in PC with Intel i5, with 2.4GHz Processor and 4GB Ram. The proposed algorithms have been tested on IEEE 9 Bus system [18].The system active demands is 315 MW. A swarm of 30 particles has been implemented on IEEE 9 Bus system as shown in Figure 1to solve the 6 different caseswith different objective functions as explained below. Table 1 and Table 2 show the input data for IEEE 9 Bus system. The results obtained are shown in Table 3.

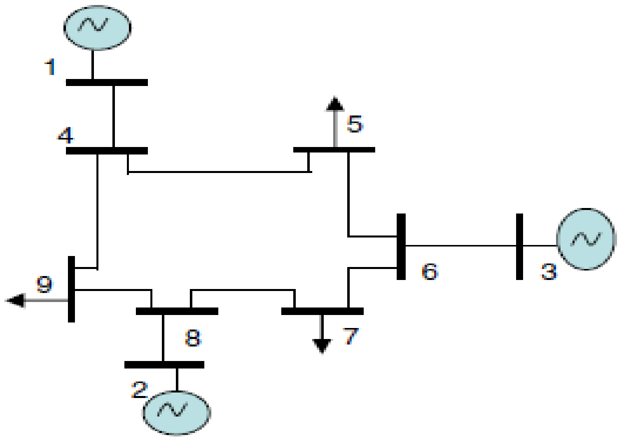

Figure 1: IEEE 9 Bus System.

Table 1.- Generator Characteristics

No. Of Buses	a_P	b_P	Cp	P_{max}	P_{min}	Q_{max}	Q_{min}
1	0.11	5	150	250	10	300	-300
2	0.08	1.2	600	600	10	300	-300
3	0.12	1	335	335	10	300	-300

Table 2. Load Characteristics.

No. Of Buses	Active Power(MW)	Reactive power(MVAR)
5	90	30
7	100	35
9	125	50

Based on the OPFP, six different cases have been investigated and are explained as below:
Case-1: Minimization of Fuel cost considering Active power (Economic Load Dispatch).

In this case the only cost considering active power generation is minimized. Losses are assumed to be zero. The objective function can be expresses as.

$$f = Min(F_1) + penalty \qquad (16)$$

Where F_1 is the cost function as shown in Eq.(1).

$$Penalty = K_p(\sum_{i=1}^{NG} P_{Gi} - P_D)^2$$

Where P_{Gi}, is the active power generation at i[th] generator bus, P_D is the Total active power demand on generators.

K_P is the penalty factor having large positive value set to 10,000.

As seen from the results shown in table 3, the Fuel cost comes out to be 5101.104 $/hr.

Case-2: Minimization of Fuel cost considering Active power (Optimal Power Flow).

In this case the cost considering active power generation is minimized based on optimal power flow solution.

$$f = Min(F_1) + penalty \qquad (17)$$

Where F_1 is the cost function as shown in Eq.(1),

$$Penalty = K_p(P_{G_S} - P_{G_S}^{\lim})^2$$

P_{G_s} is the generation at slack bus, $P_{G_S}^{\lim}$ is the generation limit at slack bus.

K_P is the penalty factor having large positive value set to 10,000.

As seen from the results (table 3) that the Fuel cost comes out to be 5209.93800 $/hr and corresponding Active power losses are 4.72022 with voltage deviation of 0.17783.

Cost in this case is increased by 2.08% than case 1 because of the presence of active power losses. Slack generator has to supply the required amount of power so that total generation at generators is equal to sum of demand and losses

Case-3: Minimization of active transmission losses.

In this case the active transmission losses are minimized. The losses are calculated using load flow equations. The objective function can be expressed as.

$$f = Min(F_2) + penalty \qquad (18)$$

Where F_2 is the fitness function representing the active transmission losses as shown in Eq.(2)

$$Penalty = K_p(P_{Gs} - P_{Gs}^{\lim})$$

K_P is the penalty factor having large positive value set to 10,000.

P_{G_s} is the generation at slack bus, $P_{G_S}^{\lim}$ is the generation limit at slack bus.

As seen from results shown in table 3, the active transmission losses are reduced by 5.05% with increase in 23.8% than case 2.

Table3: OPF results obtained for IEEE 9bus system considering Active power generation

Gen. No.	CASE1	CASE2	Case 3	CASE4	CASE 5	CASE 6
	AP(P_{gi}) MW	AP(P_{gi}) MW	AP(P_{gi}) MW	AP(P_{gi}) MW	AP(P_{gi}) MW	AP(P_{gi}) MW
1	83.396990	87.544440	152.6393	141.022300	123.518100	141.569900
2	138.463700	138.355300	81.78902	93.453880	108.523500	93.102250
3	93.139330	93.679070	84.11395	84.111980	86.758820	83.911670
Cost($/hr)	**5101.104**	**5209.938000**	5977.494	**5721.639000**	**5443.254000**	**5731.489000**
Active Loss	-	4.72022	**3.595**	**3.6334**	3.8429	**3.6313**
∑Voltage Deviation(PU)	-	0.17783	0.156	0.16486	**0.15575**	**0.15790**
Time(seconds)	10.45	13.56	23.51	29.37	26.33	31.30

Case-4: Minimization of Fuel cost considering active power and active transmission losses.

In this case both cost and transmission losses are considered simultaneously. The objective function can be expressed as.

$$f = (F_1) + \lambda_{P_L}(F_2) + penalty \qquad (19)$$

Where F_1 is the cost function as shown in Eq.(1), F_2 is the active transmission losses function as shown in Eq.(2).

λ_{p_L} is the weighting factor, which are selected 1,000 in this case

$$Penalty = K_p(P_{Gs} - P_{Gs}^{\lim})$$

K_P is the penalty factor having large positive value set to 10,000.

P_{G_s} is the generation at slack bus, $P_{G_S}^{\lim}$ is the generation limit at slack bus.

As seen from the results (table 3), the fuel cost increased by 8.94% with 23.02% decrease in transmission losses as compared to case 2.

Case-5: Minimization of Fuel cost considering active power and voltage deviation.

In this case Multi objective function is proposed in order to minimize the fuel cost and improve the voltage profile. The objective function can be expressed as.

$$f = Min(F_1) + \lambda_{vd}(F_3) + penalty \qquad (20)$$

Where F_1 is the cost function as shown in Eq.(1), F_3 is the voltage deviation function as shown in Eq.(3).

λ_{vd} is the weighting factor, which is selected 1000 in this case

$$Penalty = K_p(P_{Gs} - P_{Gs}^{\lim})$$

K_P is the penalty factor having large positive value set to 10,000.

P_{G_s} is the generation at slack bus, $P_{G_S}^{\lim}$ is the generation limit at slack bus.

As seen from the results (Table3), the voltage deviation is reduced by12.41% with increase in 4.28% in cost than case 2.

Case-6: Minimization of Fuel cost considering active power, Voltage deviation and active transmission losses.

In this case 3 conflicting objectives such as fuel cost, voltage deviation and active transmission losses are minimized simultaneously. The objective function can be expressed as.

$$f = (F_1) + \lambda_{P_L}(F_2) + \lambda_{vd}(F_3) + penalty(\$/hr) \qquad (21)$$

Where F_1 is the cost function as shown in Eq.(1), F_2 is the active transmission losses function as shown in Eq.(2), F_3 is the voltage deviation function as shown in Eq.(3).

λ_{vd}, λ_{p_L} are weighting factor, which are selected 2,000, 1500 in this case

$$Penalty = K_p(P_{Gs} - P_{Gs}^{\lim})$$

K_P is the penalty factor having large positive value set to 10,000.

P_{G_s} is the generation at slack bus, $P_{G_S}^{\lim}$ is the generation limit at slack bus.

As seen from result (Table3), voltage deviation and transmission losses are reduced by 11.2% and 23% with increase in 10% in fuel cost than case 2.

VI. CONCLUSION

In this paper different cases related to OPFP have been discussed. PSO algorithm is applied to solve such problems. Developed algorithm based on PSO is tested on IEEE 9bus system. Furthermore 6 cases related to minimization of fuel cost, voltage deviation and transmission loss has been solved. Obtained results show its effectiveness and robustness. In future the developed algorithm can be tested on large power network systems by incorporating the effect of tap changing transformers, shunt var compensators and varying the generator voltages etc.

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