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Enhancement of Power System Security by Particle Swarm Optimization Based Optimal Power Flow

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Abstract— This paper proposes an algorithm to solve the Optimal Power Flow (OPF) problem with an objective of enhancing the security of power system. The proposed approach uses Particle Swarm Optimization (PSO) algorithm to obtain the optimal power dispatch meeting steady state security constraints under various loading conditions. This PSO based OPF algorithm computes the optimal generation schedule and effectively relieves line flow violations under different single line contingencies. The efficacy of proposed algorithm is illustrated by carrying simulation studies on IEEE 30 bus system .This analysis reveals that the proposed algorithm is quite simple and efficient for solving OPF problem.

Index Terms— Contingencies, Optimal Power Flow, Particle Swarm Optimization, Power System Security, and Severity Index.

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1 INTRODUCTION

THE problem of security assessment and control has obtained much attention in the modern power industry. Security assessment [1] calculations are carried out in system planning and operation considering as series of contingencies involving credible outages of transmission circuits and generating plant. Any insecurity detected by the security assessment must be corrected in the base-case operating condition. Therefore security assessment deals with determining whether or not the system operating in a normal state can withstand contingencies without any limit violation.

The primary goal of an Optimal Power Flow [2] is to minimize the total production costs of the entire system to serve the load demand for a particular power system while maintaining the security of the system operation. The production costs of electrical power systems may depend on the situation, but in general they normally mean to the cost of generating power at each generating unit of power plants. This operation is subjected to keep each device in the power system within its desired operation range at steady-state. This will include maximum and minimum outputs for generators, maximum MVA flows of power transmission lines and transformers, as well as system bus voltages within specified ranges.

In general formulation, the Optimal Power Flow problem is a nonlinear, non-convex, large scale, static optimization problem. Many conventional programming techniques such as Linear Programming, Non-Linear Programming, Quadratic Programming, Newton Method and Interior Point Methods have been applied to solve the OPF problem effectively [3]-[5]. The Interior Point Methods also have drawbacks such as improper step size selection may cause the sub-linear problem to have a solution that is infeasible in the original nonlinear domain [6]-[7]. However, these traditional optimization methods are limited in handling algebraic functions.

In this paper, a new formulation and solution approach based on the Particle Swarm Optimization (PSO) is proposed to overcome the drawbacks of traditional methods. PSO is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995 [8]. This Method combines social psychology principles and evolutionary computation to motivate the behavior of organisms such as fish schooling, bird flocking, etc. PSO has been discovered to have better convergence performances than traditional methods [9].

PSO can be used to solve many complex optimization problems which are non linear, non differentiable and multi modal. Unlike mathematical programming methods, PSO is not sensitive to starting points and forms of objective function. Unlike other evolutionary algorithms, PSO is capable of evolving toward global optimum with a random velocity by its memory mechanism and has better global search performance with faster convergence [10]-[12].

In this paper, Particle Swarm Optimization is developed to effectively solve the optimal power flow problem incorporating a set of security constraints. Simulations for PSO based OPF are carried out on IEEE 30-bus system with an objective of improve power system security.

The paper is organized as follows; Section II describes the formulation of Optimal Power Flow problem. Section III presents Particle Swarm Optimization. Section IV describes com-

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putational procedure for solving the problem. Section V contains simulation results followed by conclusion.

2 FORMULATION OF OPTIMAL POWER FLOW PROBLEM

The OPF problem is to optimize the steady state performance of a power system in terms of an objective function while satisfying several equality and inequality constraints. Mathematically, the OPF problem can be formulated as given

$$\text{Min } F(x, u) \tag{1}$$

$$\text{Subject to } g(x, u) = 0 \tag{2}$$

$$h(x, u) \leq 0 \tag{3}$$

where *x* is a vector of dependent variables consisting of slack bus power P_{G_1}, load bus voltages V_L, generator reactive power outputs Q_G, and the transmission line loadings S_l. Hence x can be expressed as given

$$X^T = [P_{G_1}, V_{L_1} ... V_{L_{NL}}, Q_{G_1} ... Q_{G_{NG}}, S_l .... S_{l_{nl}}] \tag{4}$$

where *NL*,*NG* and *nl* are number of load buses, number of generators and number of transmission line respectively. *u* is the vector of independent variables consisting of generator voltages V_G, generator real power outputs P_G except at the slack bus P_{G_1}, transformer tap settings *T*, and shunt VAR compensations Q_C .Hence *u* can be expressed as given

$$U^T = [V_{G_1} .... V_{G_{NG}}, P_{G_2} ... P_{G_{NG}}, T_1 ... T_{NT}, Q_{C_1} ... Q_{C_{NC}}] \tag{5}$$

where *NT* and *NC* are the number of the regulating transformers and shunt compensators respectively. *F* is the objective function to be minimized, g is the equality constraints that represent typical load flow equations and *h* is the system operating constraints.

The severity of a contingency to line overload may be expressed in terms of the Severity Index, which express the stress on the power system in the post contingency period. In order to evaluate the security of the power system network a Severity Index was proposed.The objective function in the proposed OPF was selected as the minimization of the proposed Severity Index. By minimizing the value of Severity Index, it can observe an enhancement in the system security. For example, in order to determine the degree of line violations at the line L_{m-n}, the following Severity Index is proposed.

$$SI_{mn} = \frac{S_{mn} - S_{mn\max}}{S_{mn\max}} \quad m,n \ \varepsilon \ \text{NB} \tag{6}$$

$$\text{Objective function } F = \min(SI_{mn}) \tag{7}$$

where

SI_{mn} : Severity Index of line overloads;
S_{mn} : The overload flow on transmission line;
NB : Set of overloaded lines.

2.1 Constraints

The OPF problem has two categories of constraints:

A.Equality Constraints: These are the sets of nonlinear power flow equations that govern the power system, i.e,

$$P_{Gm} - P_{Dm} - \sum_{n=1}^{l} |V_m||V_n||Y_{mn}| \cos(\theta_{mn} - \delta_m + \delta_n) = 0 \tag{8}$$

$$Q_{Gm} - Q_{Dm} + \sum_{n=1}^{l} |V_m||V_n||Y_{mn}| \sin(\theta_{mn} - \delta_m + \delta_n) = 0 \tag{9}$$

Where P_{Gm} and Q_{Gm} are the real and reactive power outputs injected at bus- *m* respectively, the load demand at the same bus is represented by P_{Dm} and Q_{Dm}, and elements of the bus admittance matrix are represented by $|Y_{mn}|$ and θ_{mn}.

B. Inequality Constraints: These are the set of constraints that represent the system operational and security limits like the bounds on the following

1) Generators real and reactive power outputs

$$P_{Gm}^{\min} \leq P_{Gm} \leq P_{Gm}^{\max} \quad , m=1,\ldots, \text{NG} \tag{10}$$

$$Q_{Gm}^{\min} \leq Q_{Gm} \leq Q_{Gm}^{\max} \quad , m=1,\ldots, \text{NG} \tag{11}$$

2) Voltage magnitudes at each bus in the network

$$V_m^{\min} \leq V_m \leq V_m^{\max} \quad , \text{m}=1,\ldots, \text{NL} \tag{12}$$

3) Transformer tap settings

$$T_m^{\min} \leq T_m \leq T_m^{\max} \quad , m=1,\ldots, \text{NT} \tag{13}$$

4) Reactive power injections due to capacitor banks

$$Q_{Cm}^{\min} \leq Q_{Cm} \leq Q_{Cm}^{\max} \quad , m=1,\ldots, \text{CS} \tag{14}$$

5) Transmission lines loading

$$S_m \leq S_m^{\max} \quad , \text{m}=1,\ldots, \text{nl} \tag{15}$$

6) Voltage stability index

$$Lj_m \leq Lj_m^{\max} , m=1,...,\text{NL} \tag{16}$$

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C. Handling of Constraints: In this paper, the constraints are incorporated into fitness function by means of penalty function method, which is a penalty factor multiplied with the square of the violated value of variable is added to the objective function and any infeasible solution obtained is rejected.

To handle the inequality constraints of state variables including load bus voltage magnitudes and output variables with real power generation output at slack bus, reactive power generation output, and line loading, the extended objective function can be defined as:

$$OF = \sum_{m=1}^{N} F_m(P_{G1}) + K_p h(P_{Gm}) + K_q \sum_{m=1}^{N} h(Q_{Gm}) + K_v \sum_{m=1}^{NL} h(|V_m|) + K_s \sum_{m=1}^{NL} h(|S_m|) \quad (17)$$

Where K_p, K_q, K_v, K_s are penalty constants for the real power generation at slack bus, the react ive power generation of all generator buses or PV buses and slack bus, the voltage magnitude of all load buses or PQ buses, and line or transformer loading, respectively . $h(P_{G1}), h(Q_{Gm}), h(|V_m|), h(|S_m|)$ are the penalty function of the real power generation at slack bus, the reactive power generation of all PV buses and slack bus, the voltage magnitudes of all PQ buses, and line or transformer loading, respectively. NL is the number of PQ buses. The penalty function can be defined as:

$$\begin{aligned} h(x) &= (x - x_{\max})^2 \text{, if } x > x_{\max} \\ &= (x_{\min} - x)^2 \text{, if } x < x_{\min} \\ &= 0 \text{, if } x_{\min} \le x \le x_{\max} \end{aligned} \quad (18)$$

Where h(x) is the penalty function of variable x, $x^{\max}$ and $x^{\min}$ is the upper limit and lower limit of variable x, respectively.

3 PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a population-based evolutionary algorithm. The PSO is developed from research inspired by choreography of fish schooling and bird flocking. Natural creatures sometimes behave as a swarm. One of the main streams of artificial life research is to examine how natural creatures behave as a swarm and to reconfigure the swarm models inside a computer. A school of fish and a swarm of birds can be modeled with such simple models. The PSO has been found to be robust in solving problems featuring nonlinearity, multiple optima, and high dimensionality through adaptation, which is derived from the social-psychological theory. PSO has been successfully applied in many areas: Function Optimization, Artificial Neural Network Training, Fuzzy System Control, and other areas where (Genetic Algorithm) GA cannot be applied.

The language used to explain the PSO follows from the analogy of particles in a swarm. These key terms are:

i. Particle (individual, agent): each individual in the swarm;
ii. Position/Location: a particle's n-dimensional coordinates which represents a solution to the problem;
iii. Swarm: the entire collection (population) of particles;
iv. Fitness: the fitness function provides the interface between the physical problem and the optimization problem. The fitness function is a number representing the goodness of a given solution given by a position in solution space;
v. Generation: each iteration of optimization procedure using PSO;
vi. pbest (particle best): the position in parameter space of the best fitness returned for a specific particle;
vii. gbest (global best): the position in parameter space of the best fitness returned for the entire swarm;
viii. Vmax: the maximum velocity value allowed in a given direction.

The velocity and position update equations are given by

$$V_m^{n+1} = wV_m^n + C_1 r_1^n (p_{bestm} - y_m^n) + C_2 r_2^n (g_{best} - y_m^n) \quad (19)$$

$$w = w_{\max} - ((w_{\max} - w_{\min})/(iter_{\max})) * iter \quad (20)$$

$$Y_m^{n+1} = Y_m^n + V_m^{n+1} \quad (21)$$

Where

C_1 : Cognition Parameter which represents how much the Particle trust its own past experience;

C_2 : Social Parameter which represents how much the particle trust the swarm;

r_1, r_2 : Random Numbers;

w : Inertia Weight;

V_m^n : The Velocity of the particle in m^th dimension;

Y_m : Position of the particle;

Each particle keeps track of its coordinates in the problem space, which are associated with the best solution (fitness) it has achieved so far, pbest. Another ''best" value tracked by the global version of the particle swarm optimizer is the overall best value, gbest, and its location, obtained so far by any particle in the swarm. The basic process for implementing the PSO is as follows:

1. Initialize the swarm of particles with random position as Y_m and velocity V_m within the solution space.

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2. Evaluate the fitness function for each particle and find out the pbest.
3. For each individual particle, compare the particle's fitness value with its pbest. If the current value is better than the pbest value, then set this value as the pbest and the current particle's position Y_m as P_m.
4. Identify the particle that has the best fitness value. The value of its fitness function is identified as gbest and its position as P_g.
5. Update the velocities and positions of all the particles.
6. If the number of iterations reaches the maximum then the gbest is the optimal solution and end of the process is reached.

4 COMPUTATIONAL PROCEDURE FOR SOLVING THE PROBLEM

The implementation steps of the proposed PSO based algorithm can be written as follows;

Step-1: Initialize the parameters such as number of particles,the size of population, initial and final inertia weight, velocity of particle, number of iterations etc.

Step-2: Assume several contingencies.

Step-3: OPF calculation with PSO for most severe contingency in order.

Step-4: If OPF is solvable go to step-2 else go to step-5.

Step-5: Checking the limit violation for security constraints. If iterations reached to its max value then go to step-6 else go to step 2.

Step-6: Stop

5 SIMULATION RESULTS

The proposed PSO algorithm for solving Optimal Power Flow problem is tested on standard IEEE 30-bus system [13]. The proposed algorithm is implemented using MATLAB software and results are tabulated.

The PSO parameters used for the simulation are summarized in TABLE 1

TABLE 2 gives the details of calculation of line flows under different overloading conditions. Here, the base load is considered as 283.4 MW. In case Ia, load on the power system is 311.74 MW, which represents 10% increment on base load. In case Ib, load is 325.91 MW, which represents 15% increment on base load. In case Ic, load is 340.08 MW, which represents 20% increment on base load. In case Id, load is 354.25 MW, which represents 25% increment on base load. Under base case condition i.e. with a load of 283.4 MW, the line flow limit of 32 MVA is not violated for line 6-8. Where as under Ia, Ib, Ic and Id cases, the line limit of line 6-8 is violated. To rectify the problem of over loading in line 6-8, PSO has been applied and generation rescheduling has been done for this particular problem. From last column of TABLE 2 it can observe that line flow limit violation of line 6-8 has been corrected with the application of PSO technique.

TABLE 1
OPTIMAL PARAMETER SETTINGS FOR PSO

Parameter	Value
Population size	20
Number of iterations	150
Cognitive constant, c_1	2
Social constant , c_2	2
Inertia weight ,w	0.3-0.95

TABLE 3 presents the comparison of control variables with and without PSO at different load conditions. From TABLE 3 it was noted that, PSO based OPF maintains security of the power system network by maintaining line flows within their limits under various loading conditions.

To check the effectiveness of the proposed algorithm, it was applied to IEEE 30 bus system under the occurance of most severe contingencies. Contingency analysis was carried out and outage of lines 1-2, 1-3, 2-5 and 4-6 are found to be most severe contingencies as they are creating overloadings on other lines. The severity of the overloading was calculated by Severity Index (SI_{mn}) and the results are reported in TABLE 4.

From TABLE 4, it can be observed that line flows are maintained at their respective limits by the application of PSO algorithm and the value of Severity Index is also reduced in comparison to that of without PSO case.

TABLE 5 presents the setting of control variables for IEEE 30-bus system with and without PSO at different line outages. From the results, it was observed that all the control variables are within limits and lines are operating within the specified line limits by application of PSO based OPF algorithm under the occurance of various severe network contingencies.

6 CONCLUSION

This paper presents an improved, simple, efficient and reliable Particle Swarm Optimization algorithm for solving Optimal Power Flow problem with increase in network load and under occurance of various contingencies. The proposed method is tested on IEEE-30 bus system and the simulation results are reported.

The PSO based Optimal Power Flow algorithm not only gives consistent convergence for standard as well as conditioned systems, but also shows better performance under critical conditions. The results show the effectiveness and robustness of the proposed algorithm to solve OPF problem.

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TABLE 2
CALCULATION OF LINE FLOWS UNDER DIFFERENT OVERLOADING CONDITIONS

	Overloaded lines		Line flow limit(MVA)	Increment in load (%)	Line flow(MVA)	
	Sending bus	Receiving bus			Without PSO	With PSO
	Normal condition		32	100	32	-----
Case Ia	6	8	32	110	32.045	13.030
Case Ib	6	8	32	115	33.584	13.651
Case Ic	6	8	32	120	35.235	12.258
Case Id	6	8	32	125	36.998	9.260

TABLE 3
COMPARSION OF LOAD FLOW RESULTS WITH AND WITHOUT PSO

Control variables	Case Ia		Case Ib		Case Ic		Case Id	
	WITHOUT PSO	WITH PSO	WITHOUT PSO	WITH PSO	WITHOUT PSO	WITH PSO	WITHOUT PSO	WITH PSO
P_1	151.142	129.27	166.660	142.51	182.298	197.93	198.057	200.0
P_2	80.0	61.52	80.0	56.38	80.0	42.75	80.00	28.21
P_3	50.0	29.70	50.0	30.03	50.0	23.77	50.0	23.84
P_4	0.0	20.86	0.0	18.91	0.0	14.40	0.0	26.89
P_5	0.0	38.34	0.0	42.17	0.0	29.94	0.0	45.04
P_6	40.0	29.25	40.0	27.15	40.0	29.1	40.0	34.93
V_1	1.06	0.9634	1.06	1.0539	1.06	0.9678	1.06	1.0244
V_2	1.04	1.0292	1.04	1.0508	1.04	1.0055	1.04	1.0418
V_3	1.01	1.0030	1.01	0.9945	1.01	0.9842	1.01	1.0054
V_4	1.01	0.9781	1.01	1.0186	1.01	1.0027	1.01	1.0411
V_5	1.08	1.0169	1.08	1.0194	1.08	1.0270	1.08	0.9978
V_6	1.07	1.0115	1.07	1.0368	1.07	1.0004	1.07	1.0183
T_1	----	1.0558	----	1.0692	----	0.9522	----	1.0347
T_2	----	0.9261	----	0.9722	----	0.9909	----	0.9223
T_3	----	0.9537	----	0.9835	----	0.9703	----	0.9503
T_4	----	1.0139	----	0.9212	----	0.9499	----	1.0087
Q_{sh1}	----	0.0274	----	0.0463	----	0.0213	----	0.0024
Q_{sh2}	----	0.0382	----	0.0056	----	0.0214	----	0.0275
Q_{sh3}	----	0.0440	----	0.0252	----	0.0352	----	0.0210
Q_{sh4}	----	0.0246	----	0.0149	----	0.0311	----	0.0362
Q_{sh5}	----	0.0183	----	0.0183	----	0.0217	----	0.0056
Q_{sh6}	----	0.0314	----	0.0174	----	0.0200	----	0.0227
Q_{sh7}	----	0.0482	----	0.0278	----	0.0374	----	0.0158
Q_{sh8}	----	0.0010	----	0.0394	----	0.0228	----	0.0258
Q_{sh9}	----	0.0354	----	0.0464	----	0.0168	----	0.0363

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TABLE 4
CONTINGENCY ANALYSIS FOR IEEE 30-BUS SYSTEM

	Line outage between buses	Over loaded lines	Line flow limit (MVA)	Line flow (MVA)		Severity Index SI_{mn}		Ranking
				Without PSO	With PSO	Without PSO	With PSO	
Case IIa	1-2	1-3	130	190.47	89.82	1.089	-0.98535	1
		3-4	130	181.45	84.78			
		4-6	90	110.52	60.43			
Case IIb	1-3	1-2	130	181.87	105.73	0.431	-0.4978	2
		2-6	65	67.11	44.77			
Case IIc	2-5	2-6	65	75.40	53.764	0.3211	-0.4449	3
		5-7	70	81.28	50.950			
Case IId	4-6	1-2	130	131.24	64.023	0.1052	-0.7691	4
		2-6	65	71.22	47.992			

TABLE 5
CONTROL VARIABLES SETTING FOR IEEE 30-BUS SYSTEM

Control variables	Case IIa		Case IIb		Case IIc		Case IId	
	Without PSO	With PSO	Without PSO	With PSO	Without PSO	With PSO	Without PSO	With PSO
P_1	190.47	89.83	180.58	102.95	184.09	113.62	177.76	93.79
P_2	48.88	79.14	48.88	58.22	48.88	52.55	48.88	80.00
P_3	21.75	25.73	21.75	35.00	21.75	35.00	21.75	34.82
P_4	12.18	22.66	12.18	26.43	12.18	14.29	12.18	28.93
P_5	21.51	50.00	21.51	0.3748	21.51	45.37	21.51	33.55
P_6	12.00	23.42	12.00	30.27	12.00	31.81	12.00	18.61
V_1	1.0700	0.9815	1.0700	1.0148	1.0700	1.0283	1.0700	1.0007
V_2	1.0538	1.0194	1.0538	1.0445	1.0538	1.0323	1.0538	1.0369
V_3	1.0299	1.0180	1.0299	0.9962	1.0299	0.9897	1.0299	1.0131
V_4	1.0346	1.0079	1.0375	0.9981	1.0468	0.9942	1.0560	0.9970
V_5	1.0404	1.0296	1.0381	1.0026	1.0412	0.9500	1.0520	1.0307
V_6	1.0469	1.0016	1.0370	1.0211	1.0375	1.0118	1.0369	0.9838
T_1	----	1.0947	----	1.0242	----	1.0015	----	0.9908
T_2	----	1.0569	----	0.9994	----	0.9000	----	1.0290
T_3	----	0.9823	----	0.9461	----	0.9773	----	0.9127
T_4	----	0.9946	----	0.9570	----	0.9338	----	0.9593
Q_{sh1}	----	0.0452	----	0.0119	----	0.0270	----	0.0500
Q_{sh2}	----	0.0105	----	0.0390	----	0.0173	----	0.0177
Q_{sh3}	----	0.0386	----	0.0214	----	0.0345	----	0.0180
Q_{sh4}	----	0.0216	----	0.0316	----	0.0196	----	0.0064
Q_{sh5}	----	0.0362	----	0.0262	----	0.0045	----	0.0419
Q_{sh6}	----	0.0495	----	0.0470	----	0.0167	----	0.0458
Q_{sh7}	----	0.0440	----	0.0261	----	0.0500	----	0
Q_{sh8}	----	0.0101	----	0.0500	----	0.0465	----	0.0490
Q_{sh9}	----	0.0315	----	0.0172	----	0.0260	----	0.0128

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