A PSO-based Approach to Determine the Market Clearing Price by Considering System Losses and Reactive Power Constraints in a Pool Market

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Abstract: The deregulation of electricity has led to significant transformations in the market structure and policies governing the industry. The primary responsibility of a power system operator in this market is to establish the Market Clearing Price (MCP). The MCP is established by evaluating the incremental bids submitted by generators in various markets. But the quadratic bid functions have more information about the price structure and are more realistic. The Independent System Operator (ISO) determines the clearing price by analyzing the bids submitted. Conventional methods do not provide an accurate calculation of MCP for the spot market. This may lead to poor allocation of generation. This paper uses the basic Particle Swarm Optimization technique to maximize the generator bid function. By calculating MCP, the optimum generation with least cost is determined. Losses in the system with reactive power constraints are considered while the loads are kept in-elastic. The result of the proposed technique is compared with the classical approach. IEEE 9 bus system is taken to illustrate the proposed model.

Keywords: **Particle Swarm Optimization (PSO); Pool market; Market Clearing Price (MCP); inelastic; Optimal Power Flow (OPF).**

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1. Introduction

In the present electricity market, the system is moving from vertically integrated structure to the deregulated market structure. Electric utilities and power system companies are forced to change to open market and the monopoly behaviour of the market has gradually changed. Developing nations have seen the rise of the deregulated electricity market due to a combination of increasing demand, poor system management, and illogical tariff policies. Developed nations prioritize supplying electricity to customers at affordable rates and expanding their options for accessing cost-effective energy sources.

Independent System Operator (ISO) is an authority responsible for the unbiased market trading. The ISO reviews the bids submitted by the entities and establishes the market price by taking into account various system constraints such as load flow, generator, and transmission line limitations.

Market Clearing Price (MCP) is the price when a market is in equilibrium. In pool markets, they operate as a common price [1] under normal condition; with system constraints, it is termed as locational pricing [2]. Lot of researches has been carried out in the area of forecasting the MCP using conventional and intelligent algorithms [3-5]. These forecasting techniques can be used by the bidders to improve their individual profit. ISO can also forecast for the welfare and security perspective of the system.

One of the main challenges in power system network is to operate the system under transmission congestion. The generation and power flow must be rescheduled for an efficient operation under congestion. The power flow must be optimized for the desired operation of the system. There are two models to find the optimum power flow (OPF), DC OPF [6-7, 9] and AC OPF [8-9]. In DC OPF, the reactive power is not considered at any point of time to find the optimum point.Because of which, the problem becomes simple and faster in convergence. The effect of reactive power is considered in the latter.

BijunaKunju and P.S.Nagendra Rao suggested a method to determine the MCP using non-linear bid functions with elastic load using conventional technique [10]. The authors have neglected the losses in the system. This drawback is eliminated by including the system losses using loss equation which is a function of active power generation [11]. In this paper, OPF from which MCP is determined using a sample metaheuristic approach, Particle Swarm Optimization (PSO). It is an intelligent algorithm better than conventional algorithms in terms of accuracy and it works on wide search area for global optima.

2.Methodology

2.1 Without considering system losses

The MCP is calculated based on the generation and consumer demand bid functions. The losses in the system due to the transmission parameters are neglected. Consider a system with *N* number of generators and *M* number of loads. The generator bid function is represented by Equation 1.

$$C_i(P_{gi}) = \mathrm{a}_i P_{gi}^2 + \mathrm{b}_i P_{gi+} c_i \quad (1)$$

where $C_i(P_{gi})$is the cost of generating i^{th} unit, a_i is the quadratic cost coefficient of unit *i*, b_i and c_i are linear and the no-load costs respectively. The generator manufacturer provides these coefficients [12].

The goal of the pool market operator is to optimize the cost function outlined in

Equation 2.

$$\sum_{i=1}^{N}\left(C_i\left(P_{gi}\right)\right) \tag{2}$$

subjected to power balance constraint as shown in Equation 3.

$$\sum_{i=1}^{N}\left(P_{gi}\right)-\sum_{j=1}^{M}\left(P_{dj}\right) \tag{3}$$

Equation 4 provides the augmented objective function for unconstrained optimization.

$$L=\sum_{i=1}^{N} C_i\left(P_{gi}\right)-\lambda\left(\sum_{i=1}^{N} P_{gi}-\sum_{j=1}^{M} P_{dj}\right) \tag{4}$$

where λ is the Lagrangian multiplier. The incremental cost of generators can be written as shown in Equation 6.

$$\frac{dC_i}{dP_{gi}}=\lambda=2a_iP_{gi}+b_i \tag{5}$$

The conditions for optimality of *L* are given by Equation 7 and 8.

$$\frac{dL}{d\lambda}=\frac{dC_i}{dP_{gi}}=\quad 0\ \forall\ i \tag{6}$$

At the point of optimization, the incremental cost functions for all generators should be equivalent to the incremental utility function for all consumers, which is also equal to λ.

$$2\mathrm{a}_iP_{gi}+\mathrm{b}_i=2\mathrm{a}_kP_{gk}+\mathrm{b}_k=\lambda\ \forall\ i \tag{7}$$

where*i, k* ∈ *N*

$$P_{gi}=\frac{2\mathrm{a}_kP_{gk}+\mathrm{b}_k-\mathrm{b}_i}{2\mathrm{a}_i} \tag{8}$$

and

$$\lambda=\frac{2P_G+B}{A} \tag{9}$$

Rearranging (9), we get,

$$P_{gi}=\frac{\lambda-\mathrm{b}_i}{2\mathrm{a}_i}\ \forall\ i \tag{10}$$

The schedules of all generators can be found out using (10)

2.2 Considering system losses and reactive power balance

The losses in the system cannot be neglected as it causes great impact on balancing the power. If losses are not considered, the demand cannot be met with allocated generation. Reactive power balance must also be considered for the efficient working of the system. The slack bus generator is mainly responsible for the active and reactive power balance in terms of losses. The primary goal of the pool market operator is to optimize the social welfare function presented in Equation 11.

$$\sum_{j=1}^{M}\left(Bf_j\left(P_{dj}\right)\right)-\sum_{i=1}^{N}\left(C_i\left(P_{gi}\right)\right) \tag{11}$$

subjected to the power balance constraint

$$\sum_{i=1}^{N}(P_{gi}) = \sum_{j=1}^{M}(P_{dj}) - P_L \quad (12)$$

$$\sum_{i=1}^{N}(Q_{gi}) = \sum_{j=1}^{M}(Q_{dj}) - Q_L \quad (13)$$

The procedure for finding MCP and scheduling of generation are same as discussed above, but the effect of losses and reactive power balance are included in this approach. Since the losses in system depend on the generations, the power flow must be optimized to find λ and generation schedule with sufficient accuracy. Conventional OPF techniques are used commonly to solve the above problem. By considering system losses along with the demand, the allocation of generation is satisfied.

3. Proposed Approach

The MCP is calculated by efficiently scheduling generators to meet both the active and reactive power demand while accounting for system losses. The OPF issue is commonly employed to calculate the most efficient allocation of generators while reducing overall operational expenses and ensuring system security requirements are met. In this paper, combination of Newton Raphsons' load flow with reactive power constraints and PSO is considered as AC-OPF problem.

Particle Swarm Optimization is a computational intelligence algorithm. It is inspired from the behaviour of birds and fish. The particles move within a setting by mimicking the more successful individuals in the group, ultimately steering their trajectory towards favorable locations. The objective of the algorithm is to guide all particles towards the optimum point within a multi-dimensional space. Initially, random positions and random velocities are allocated to each particle in the space. Following every position update, the objective function undergoes sampling. The convergence of particles towards optimal solutions is achieved by a blend of exploring new possibilities and exploiting the already identified favorable positions within the search space. The flowchart of PSO is shown in Fig 1.

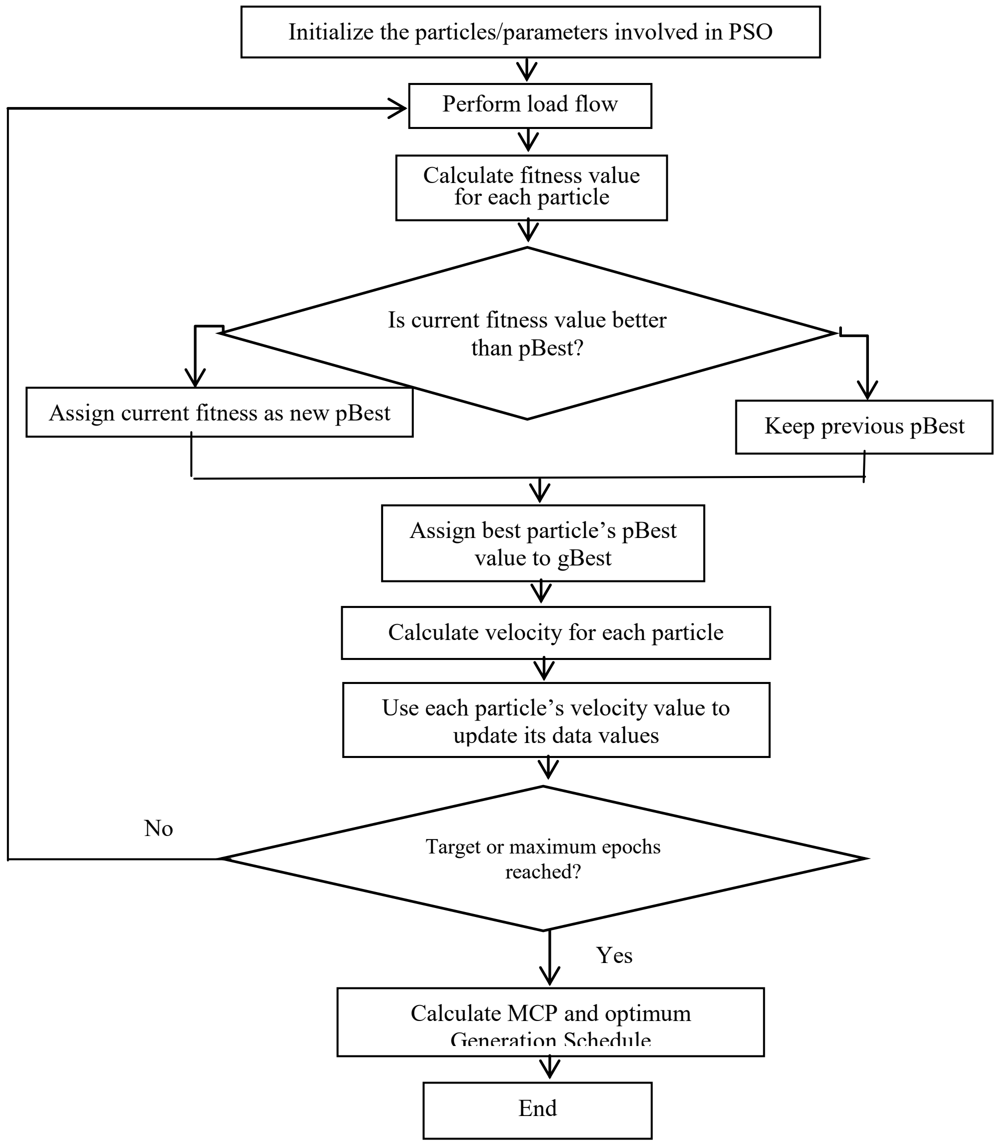

Fig. 1. Flowchart of Particle Swarm Optimization

The primary goal of this issue is to optimize the social benefit function through the reduction of total costs while adhering to energy balance and other system constraints. Power flow is obtained by AC OPF model under the assumption of no transmission congestion. Objective function is

$$\text{Minimize } \sum_{i=1}^{N}\left(C_i\left(P_{gi}\right)\right) \tag{14}$$

subjected to power balance constraints

$$\sum_{i=1}^{N}(P_{gi}) = \sum_{j=1}^{M}(P_{dj}) - P_L \quad (15)$$

$$\sum_{i=1}^{N}(Q_{gi}) = \sum_{j=1}^{M}(Q_{dj}) - Q_L \quad (16)$$

Generator operating limit constraints

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad (17)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad (18)$$

Voltage limit constraints

$$V_k^{min} \leq V_k \leq V_k^{max} \quad (19)$$

Voltage angle constraint

$$\theta_{mn}^{min} \leq \theta_m \leq \theta_{nm}^{max} \quad (20)$$

In this case, the fitness value is the total system cost which is calculated based on the optimal power flow and scheduling of generation. Initially, all the particle velocity is assumed to be zero. The fitness value is calculated for every particle (power generation) and checked for its optima. If new optimum is reached, the position and velocity of the particle is updated. All particles move towards the optimal point with the updated velocities. The iteration will stop when a maximum number of iterations are exceeded or when an acceptable solution is reached.

4.Results and Discussion

4.1 Test system

Standard IEEE 9-bus system is used as the test system to determine the MCP. In this system, there are three generators and three consumers. The active and reactive power demand in this system is fixed. The total generation of power is equal to the sum of demands and the network losses. The generator, line and load data of the test system is given in Table 1 and Table 2.

Table 1. Load and bus data of IEEE 9 bus.

Bus	P (load) (MW)	Q(load) (MVAR)	Voltage (kV)	Bus voltage (pu)
1 (slack)	---	---	16.5	1.04
2	---	---	18	1.025
3	---	---	13.8	1.025
4	---	---	230	1
5	125	50	230	1
6	90	30	230	1
7	---	---	230	1
8	100	35	230	1
9	---	---	230	1

Table 2. Line data of IEEE 9 bus.

Line	Half line charging admittance-p.u.	Reactance in p.u.	Resistance in p.u.
1-4	0	0.0576	0
4-5	0.176	0.085	0.01
4-6	0.079	0.092	0.017
3-9	0	0.0586	0
6-9	0.179	0.17	0.039
5-7	0.153	0.161	0.032
7-8	0.0745	0.072	0.0085
2-7	0	0.0625	0
8-9	0.1045	0.1008	0.0119

The generator cost function is represented by quadratic functions. The cost functions of generators are as follows. $C_1 = 0.003P_{g1}^2 + 2P_{g1} + 80$ Rs/hr, $C_2 = 0.015P_{g2}^2 + 1.45P_{g2} +100$ Rs/hr and $C_3 = 0.01P_{g3}^2 + 0.95P_{g3} +120$ Rs/hr.

4.2 Test Results

The optimum generation with least cost is determined by solving the OPF using Particle Swarm optimization technique. The total system cost and active power generation of all generators are determined for the proposed system. The result obtained is compared to the same test system without system losses and with system losses (using conventional technique). The total demand in the test system is 315 MW in all the cases and it remains inelastic throughout the analysis. Using the PSO algorithm, the generation is allocated in such a way that, the total cost of generation is made minimum. By this optimum allocation of generation, the total generation is made optimum by satisfying all the system constraints. The total loss in the system is also reduced compare to the conventional optimization technique. The comparison of the output obtained is shown in table 3.

CASE 1: Considering without losses

CASE 2: Considering losses (Linear programming (LP) method)

CASE 3: Proposed system - Considering losses (using Particle Swarm Optimization)

Table 3. Comparison of results

	CASE 1	CASE 2	CASE 3
P_{g1} (MW)	162.77	165.2084	164.1014
P_{g2} (MW)	50.88	51	51.9945
P_{g3} (MW)	101.33	101.6593	101.6342
Total P_g(MW)	315	317.8677	317.7301
System load (MW)	315	315	315
Total losses (MW)	-	2.8677	2.7301
MCP (Rs/MWh)	2.9767	2.9912	2.9846
Total Cost (Rs)	1016.57	1025.1857	1024.7816

The PSO parameters are shown in Table 4. These parameters are selected experimentally. Generators at bus 2 and 3 are taken as the variable in PSO with Generator at bus 1 is the slack bus. The three generators schedules are determined such that the total generation cost is minimum. The number of particles initialized is 200. The particles converge faster as the number of particles increases.

Table 4. PSO parameters

Number of dimension	2
Swarm size	200
Maximum iteration	80
Inertia weight factor	0.8
Weighting factors	2
Velocity of particle	-30 to 30

The convergence graph of PSO for the proposed method (Case 3) is shown in fig 2.

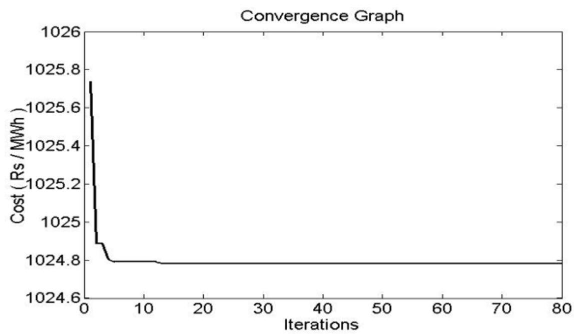

Fig. 2. Convergence graph

5. Conclusions

This paper showcases a successful approach for calculating the market clearing price through the utilization of Particle Swarm Optimization technique. Since PSO is an intelligent algorithm, the optimum value is reached with high accuracy and fast convergence. Improved scheduling of power generation decreases both the overall generation and system expenses. Hence, the market equilibrium price is efficiently determined.The result of the proposed technique is compared with the conventional technique. The result obtained is promising since the total generation as well as system losses were reduced and thus huge amount of fuel as well as money is saved. The same problem can be extended for an elastic load which reflects the exact societal welfare function.

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