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Pricing of Reactive Power Service in Deregulated Electricity Markets Based on Particle Swarm Optimization

M. Sedighizadeh, A. Rezazadeh and M. Seyed Yazdi

Abstract—**This study presents a new evolutionary method for reactive power pricing based on optimal power flow. Adequate reactive power is one of the most important parameters for secure operation of power system. In restructured electricity market, power system is operated near its secure boundaries in order to maximize social welfare. So Appropriate and accurate pricing of this service, can be very considerable in this environment. The main purpose of this paper is usage of Particle Swarm Optimization method for determination active and reactive power prices produced by generators, based on Locational Marginal Price (LMP). The proposed method has been applied on IEEE 14 bus system and compared with GA.**

Index Terms—**Reactive power pricing, particle swarm optimization, genetic algorithm, locational marginal price, restructured power market.**

I. Introduction

Because of competitive structure of energy markets, reduction of regulations in load area and more motivation for using available transmission systems facilities, power system is utilized near its secure boundaries. Considerably ancillary services that provide reliability and voltage security become very important in deregulated environment. Reactive power is one of the most important ancillary services in power system because during normal operations, it is required to maintain the necessary balance between generation and load in real time, to maintain voltages within the required ranges and to transmit active power. Therefore Reactive power value and its influence on system stability, especially during hard and congested conditions, can be very high [1]. Lack of reactive power can make voltage collapse that it is the main reason of recent widespread power outages worldwide such as one occurred in the United States and Canada in 2003 [2].

Appropriate and accurate pricing of this service not only covers the costs of reactive power supplying and provides incentives for investment of reactive power equipment so as to maximize overall social welfare, but also gives useful information about necessity of reactive power supporting and voltage control to system operator.

Until now different pricing methods is proposed for pricing this service but some of the proposed methods are usually difficult and hard in practice. Reference [3] presents the analysis of the dominant component determined from the opportunity costs of a generator in the real power markets in the cost structure of this service. Reference [4] suggests a new approach for reactive power pricing that is especially suitable for a power market using pool model. Reference [5] devises a scheme enforced capital investment on the needed services. In that scheme reactive support of generators is divided into two functions: reactive power delivery and voltage control. Some papers try to estimate reactive power price via classifying reactive power costs [6]. Reactive power pricing is principally based on the costs of reactive power providing that it can be achieved directly by determining marginal cost of reactive power or from market by using supply and demand curve [1]. In mentioned paper the combined reactive power market model is proposed for reactive power pricing. Spot pricing theory which its purpose is maximizing social welfare is proposed by F. C. Shewepp and et al. [7].In that paper for the first time marginal price concept from microeconomics introduced in power systems and used in electricity spot pricing. Nodal pricing among the other schemes based on locational marginal costs of system is most considerable. With nodal pricing of reactive power, prices at each node on a network reflect the marginal cost of generating that power. To estimate these costs, Optimal Power Flow (OPF) which its goal is minimization system operational costs subject to system operational constrains, is used. Two algorithms for solving optimal power flow (OPF) have been presented by [8]: genetic algorithm and ant colony algorithm.

In this study, a new approach based on Locational Marginal Price (LMP) for solving OPF in order to minimize objective function and therefore maximize social welfare is presented which results LMP of those powers in each node of system. The objective function is including cost of active and reactive powers produced by generators. The mentioned method is studied on 14-bus IEEE standard network and the results are compared to Genetic algorithm to approve these results are reasonable and practical.

II. Problem Formulation

OPF problem is a nonlinear optimization problem which its goal is minimizing objective function subject to equality and inequality constrains. There are many methods to optimize non linear problems. In this study Particle Swarm Optimization algorithm (PSO) is applied in solving the OPF problem.

A. Particle Swarm Optimization

Particle swarm optimization is a population based

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M. Sedighizadeh is with Faculty of Engineering and Technology, Imam Khomeini International University, Ghazvin, Iran. (m_sedighi@sbu.ac.ir)
A. Rezazadeh and M. Seyed Yazdi are with Shahid Beheshti University, Tehran, Iran.

optimization method which was proposed by Kennedy and Eberhart in 1995 [9]. This algorithm considers some particles. Each particle is a candidate for solution in the search space restricted by problem constrains. The particles try to find problem optimal solution moving in the space. As presented in (1) next position of each particle is determined stochastically according to its own previous position, best solution for optimized problem found by itself and best solution found by whole group.

$$x_{i+1} = v_i + x_i \tag{1}$$

V_i is determined by (2) where $rand_1$ and $rand_2$ are random numbers between 0 and 1, c_1, c_2 are constant number that is typically in the range [0.5 - 2] and w is inertia coefficient which it is important for PSO's convergence that it is usually defined as (3) where constant coefficients $\omega_{\max}$, $\omega_{\min}$ are the maximum and minimum inertia coefficients, respectively. *iter* is represented the number of iteration and max_{iter} is maximum number of iteration.

$$\vec{v}_i = \omega.\vec{v}_i + c_1.rand_1.(p_i - x_i) + c_2.rand_2.(g_d - x_i) \tag{2}$$

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{\max_{iter}} \times iter \tag{3}$$

Some important advantages of PSO algorithm rather than other evolutionary approach such as Genetic Algorithm are simple implementation and high speed execution in order to find optimal solution [10].

B. Objective Function

As presented in (4), objective function used in this case consists of active and reactive power production cost produced by generators. Consider a network that in it N and N_g are number of buses and number of generator buses respectively.

$$C = \sum_{i \in Ng} \left[C_{gpi}(P_{Gi}) + C_{gqi}(Q_{Gi}) \right] \tag{4}$$

Subject to power flow equality and inequality constrains:

$$P_{Gi} - P_{Di} - \sum_{j \in N} |V_i||V_j||Y_{ij}| Cos(\theta_{ij} + \delta_j - \delta_i) = 0 \tag{5}$$

$$Q_{Gi} - Q_{Di} - \sum_{j \in N} |V_i||V_j||Y_{ij}| Sin(\theta_{ij} + \delta_j - \delta_i) = 0 \tag{6}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad i \in N_G \tag{7}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad i \in N_G \tag{8}$$

$$|P_{ij}| \le P_{ij}^{\max} \quad i \ne j \quad i, j \in N \tag{9}$$

$$V_{i,\min} \le V_i \le V_{i,\max} \tag{10}$$

Where

P_{Gi}, Q_{Gi} real and reactive power generation at i^{th} bus

P_{Di}, Q_{Di} real and reactive power demand at i^{th} bus

$C_{gpi}(P_{Gi})$ active power cost function in i^{th} bus

$C_{gqi}(Q_{Gi})$ reactive power cost function in i^{th} bus

For computing Cost function of active power (11) is regarded.

$$C_{gpi}(P_{Gi}) = aP_{Gi}^2 + bP + c \tag{11}$$

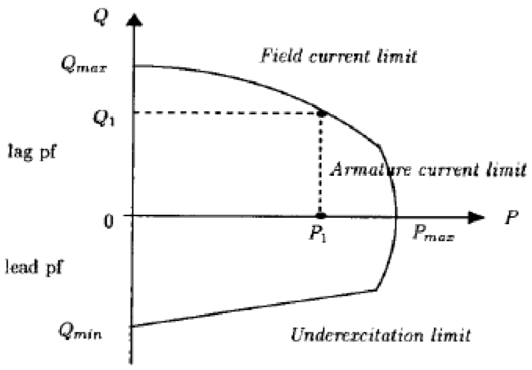

Fig. 1. Loading capability diagram.

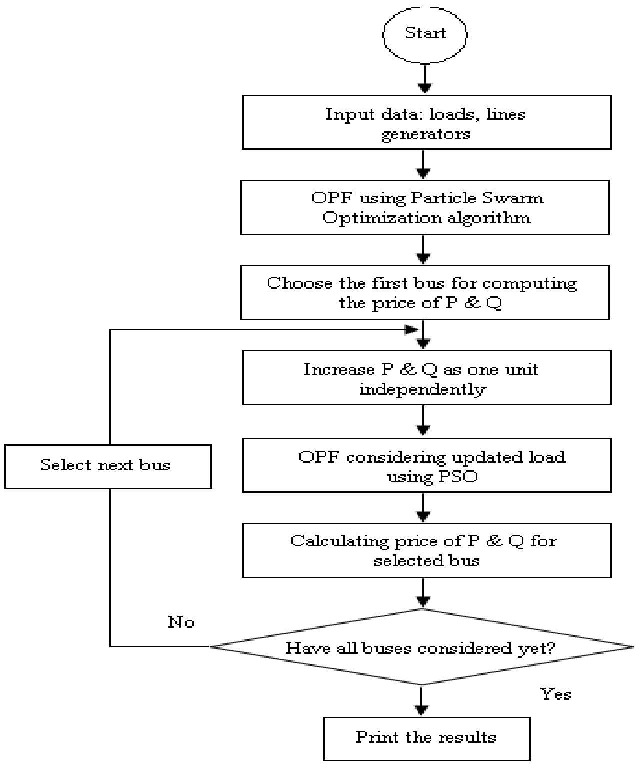

Fig. 2. The flow chart of active and reactive power pricing

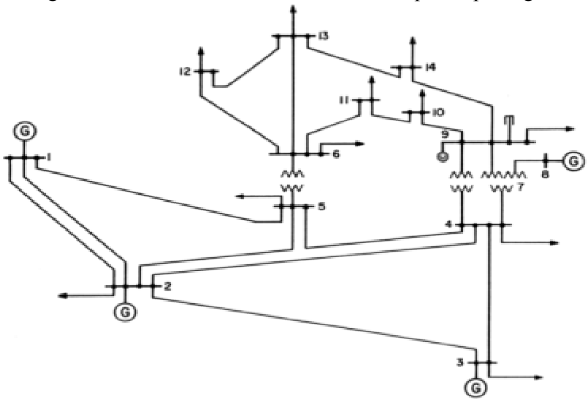

Fig. 3. IEEE 14-bus system.

Cost function for reactive power produced by generator is based on opportunity cost deduced via loading capability diagram shown in Fig. 1. Essentially opportunity cost is based on market process, but since it is hard to determine its precise and exact value, in this paper its simplest form is used where Q_{Gi} and $S_{Gi,\max}$ are reactive power of generator in i^{th} bus and maximum apparent power in i^{th} bus, respectively. K is reactive power efficiency rate which is usually between 5-10% which in this paper K = 5% is considered.

$$C_{gqi}(Q_{Gi}) = \left[C_{gpi}(S_{Gi,\max}) - C_{gpi}(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2}) \right] K \qquad (12)$$

C. *Flowchart and methodology*

In this paper Locational marginal price (LMP) method is used for active and reactive power pricing. As illustrated in Fig. 2 Active power prices in each bus is determined from difference between optimum cost while constant loading and optimum cost while active power demand increases 1MW in subjected bus. Reactive power prices in each bus is determined from difference between optimum cost while constant loading and optimum cost while reactive power demand increases 1MVAr in subjected bus.

III. Test Results

PSO optimization method has been applied on IEEE 14 bus system which its single lines diagram shown in Fig. 3. Table I and Table II list the line parameters of network and characteristics of the network loads, respectively. Cost function coefficients of active power production by generators are in Table III. In this study mentioned objective function is calculated for 3 cases:

1) By the system base load that totally is 259 MW and 73.5 MVAr.
2) 40 MVAr reactive powers in bus 2, 3, 4 and 50 MVAr in bus 5 are injected. These buses are selected because they consume more VAr in respect of others.
3) Active demand loads in all buses are increased by 1.2.

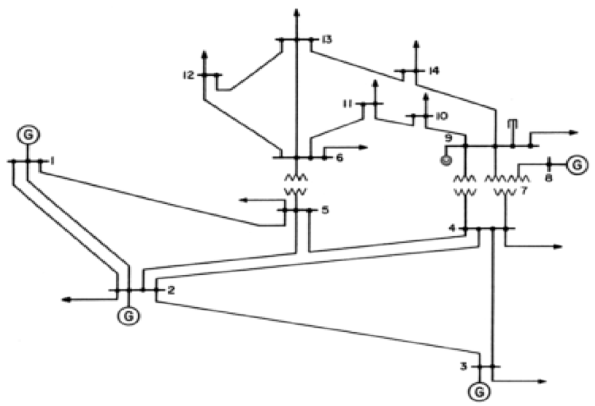

Fig. 3. IEEE 14-bus system.

Then the determined prices by PSO optimization method are compared with those are calculated by Genetic Algorithm (GA) method in Table IV where parameter λ presents the price of active and reactive power produced by generators. Case 2 declares when reactive power is injected to system in critical buses the price of active power is reduced but in this system the prices of reactive power is nearly constant in respect of case 1. Case 3 shows that, in this network, when active demands are increased, the prices of generator active power are increased too. As can be seen the result determined by PSO optimization method are reasonable and approximately equal to ones determined by GA.

TABLE I Line Parameters of 14 Bus IEEE Network

From	To	R (Ω)	X (Ω)	Y_c (S)
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
2	3	0.04699	0.19797	0.0438
2	4	0.05811	0.17632	0.034
2	5	0.05695	0.17388	0.0346
3	4	0.06701	0.17103	0.0128
4	5	0.01335	0.04211	0
4	7	0	0.20912	0
4	9	0	0.55618	0
5	6	0	0.25202	0
6	11	0.09498	0.1989	0
6	12	0.12291	0.25581	0
6	13	0.06615	0.13027	0
7	8	0	0.17615	0
7	9	0	0.11001	0
9	10	0.03181	0.0845	0
9	14	0.12711	0.27038	0
10	11	0.08205	0.19207	0
12	13	0.22092	0.19988	0

TABLE II Load Characteristics

Bus	Active power (MW)	Reactive Power (MVAr)
1	0	0
2	21.7	12.7
3	94.2	19
4	47.8	-3.9
5	7.6	1.6
6	11.2	7.5
7	0	0
8	0	0
9	29.5	16.6
10	9	5.8
11	3.5	1.8
12	6.1	1.6
13	13.5	5.8
14	14.9	5

TABLE III
Generators Characteristics

Generator	a($/H)	b($/H)	c($/H)	P_{max}(Mw)	P_{min}(Mw)
1	0.11	2	150	332.4	0
2	0.25	5	225	140	0
3	0.09	1.2	600	100	0
6	0.04	1	335	100	0
8	0.10	3	400	100	0

TABLE IV RESULT AND COMPARISON

	Case 1		Case 2		Case3	
	PSO	GA	PSO	GA	PSO	GA
Min cost($/H)	3441.9	3440.1	3446.1	3435.9	4137.7	4136.01
λ_{P1}($/H MW)	11.6	11.62	10.1377	11.713	14.5078	15.482
λ_{P2}($/H MW)	11.66	11.75	10.2708	11.683	14.7849	14.7743
λ_{P3}($/H MW)	11.86	12.03	10.2930	11.93	15.0735	15.1429
λ_{P4}($/H MW)	11.32	11.41	10.0259	11.482	14.4192	14.401
λ_{P5}($/H MW)	12	11.91	10.3959	11.970	14.9521	14.9978
λ_{Q1}($/H MVAr)	0.18	0.334	1.5296	0.171	0.1363	0.3289
λ_{Q2}($/H MVAr)	0.08	0.325	1.9691	0.388	0.1547	0.3359
λ_{Q3}($/H MVAr)	0.12	0.268	1.8442	0.229	0.1354	0.2722
λ_{Q4}($/H MVAr)	0.18	0.012	1.6143	0.093	0.1621	0.0213
λ_{Q5}($/H MVAr)	0.02	0.213	1.6814	0.095	0.2879	0.2414

IV. CONCLUSION

This paper use Particle Swarm Optimization method for solving Optimal Power Flow (OPF) in order to minimize the objective function which consists of active and reactive power costs produced by generators. Particle swarm optimization is a very simple algorithm that appears to be effective for optimizing a wide range of functions [9]. This approach has been applied on IEEE 14 bus system. The simulation results of this work in comparison with Genetic algorithm show that the method is physically reasonable and its implementation is simpler than other optimization methods such as GA. The presented technique can also be applied to manage and set the price of the reactive power supplied by other sources than generators and in different market types.

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