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# Application of VEPSO Optimization Algorithm to Reactive Power Pricing in an Electricity Market

Sajjad Asadollahi Koulani, Davar Mirabbasi

*Islamic Azad University of Ardabil, Ardabil*

## Abstract

Reactive power service is one of the most important ancillary services in electricity market that play important role in security and reliability of network. In the modern power systems, voltage stability analysis and evaluation of security margin is necessary for avoid of instability and voltage collapse phenomenon. Reactive power pricing in the competitive environment is important problem that with maintaining system security, provide the economic signal for investors to exploitation system. In this paper, the VEPSO algorithm is used to optimal pricing of reactive power. The presented model for calculation of the active and reactive power marginal prices of generators and capital cost of capacitors has been used an optimal power flow is based on VEPSO algorithm which the objective function minimizes the active and reactive power production cost. Test results show the reactive power production cost and the capital investment of capacitors should be considered in reactive power pricing for their noticeable impacts on reactive power marginal price. The approach presented provide a useful tool to answer the question whether to pay the reactive power charge or whether it is more profitable to make a capital investment in reactive compensation equipment. Simulation results show that effective performance of VEPSO algorithm in optimization of cost objective function of reactive power.

**Keywords:** VEPSO, Reactive Power Pricing, Electricity Market

## Introduction

The primary function of an electrical power system is to meet users 'demands at the lowest cost with a satisfactory expectation of continuity of supply and sufficiently small deviation in frequency and voltage. Under normal conditions the continuous adjustment of the generation of active and reactive power to variations in power demand ensures that the system functions correctly, this being characterised by a constant frequency and by voltage values at each busbar of the system in which variations are maintained within permissible limits. The conditions for this adjustment are different for the frequency and for the voltages. In fact, an overall balance of generation and demand of active power maintains the same frequency everywhere, whereas the voltages can be controlled between admissable limits of variation only by local equilibrium of generation, consumption and exchange of reactive power. The problem of voltage and reactive power control in power systems is concerned with the voltage quality, increased security and improved system economy aspects. In terms of voltage quality, the scheme should ensure that system voltages are maintained within operational criteria. The upper limits are determined by the necessity to avoid transformer saturation and to keep voltages under rated values that the insulation materials can withstand without damage, while the lower limits mainly come from security constraints, so as to avoid overloads, to preserve the steady-state stability. From the point of view of increased security, the scheme should make optimum use of the available reactive power sources and hence, by increasing reactive reserves, enhance the ability of the system to respond to unexpected events. Effective voltage control across the system is achieved by the balancing of reactive power.This procedure is necessarily more complicated than the corresponding balancing of active power because of the widely variable requirements of the transmission network over the full range of system loading and operating conditions [1,2].

Recentlly, The conventional structure of electric power system the world is transforming into a competitive electricity market and planning and operation of modern power system is primarily based on economic perspective.Until now, effort has been directed primarily toward developing methodologies to determine remuneration for the active power of the generators. Although the investment in electric power generation and the fuel cost, represent the most important costs of power system operation, reactive power is becoming more and more important, especially from the security point of view and the economic effect caused by it [3]. herfore, reactive power management is essential to transfer real energy and support power system security.Developing an accurate and feasible method for reactive power pricing is important in the electricity market. From the review several diverse methods for handling reactive power within the deregulated market framework emerges. While in many of the markets, proper financial compensation mechanisms exist to compensate the providers for their service, some others continue to handle reactive power through regulatory frameworks and technical operation guidelines. The reactive power management and payment mechanisms however,

vary for each deregulated electricity market in the way the contracts are framed and the markets are operated. Usually the independent system operator (ISO) enters into contracts with reactive power providers for their service provisions. In the past, some literature has discussed reactive power as an identifiable ancillary service [4], and some papers consider the reactive power cost allocation [5-8]. In example, in the US context, as per the NERC's Operating Policy-10 [9], only that reactive power provided by synchronous generators are considered as ancillary services and can receive financial compensation for their services. This is also true for the UK and Australian markets.The Australian market additionally considers reactive power from synchronous condensers also as ancillary service [10]. Most authors try to estimate reactive power costs directly from generator information; some others try to infer the value of generator reactive power services from the cost of other reactive power sources, other approaches use relative real and reactive power capacities to infer their relative costs.

A summary of existing policies for real-time pricing rates is presented in reference [11]. Most findings in real-time pricing of reactive power are closely related to those of active power pricing. Little attention has

been given to pricing of reactive power, even though it is an established fact that the flow of reactive power affects both real line losses and voltage magnitudes. One reason for this is the inherent difficulty in understanding the concept, especially by economists. Modifications of optimal power flow (OPF) models are used in [12-13] to calculate real-time pricing of real and reactive power. In [14], the effect of optimally located FACTS devices on real time prices has been studied.A mixed integer nonlinear programming (MINLP) based model is proposed for optimal placement of FACTS devices along with calculating active and reactive power marginal prices and the impact of placing FACTS devices on marginal prices is observed.The Trust-region-based augmented Lagrangian method (TRALM), step-controlled primal-dual interior point method (SCIPM), and constrained cost variable (CCV) OPF formulation are proposed in [15]. The accuracy of voltage magnitude given by power flow method is nessecery for reactive power market so, the contribution of the [16] is the development of a new DCQF method which can be built into a DC Optimal Q Flow Method for pricing of pure reactive power market.

In this paper,the VEPSO algorithm is used to optimal pricing of reactive power. the presented model for calculation of the active and reactive power marginal prices of generators and capital cost of capacitors has been used an optimal power flow is based on VEPSO algorithm which the objective function minimizes the active and reactive power production cost.

## Problem Formulation

The power transmission capability available from a transmission line design is limited by technological and economical constraints. Therefore, in order to maximize the amount of real power that can be transferred over a network, reactive-power flows must be minimized. Consequently, sufficient reactive power should be provided locally in the system to keep the bus voltages within nominal ranges in order to satisfy customers' equipment voltage ratings. The reactive devices have different characteristics in terms of dynamics and speed of response, ability of voltage changes, capital costs, operating costs, and opportunity costs. In vertically integrated electricity systems, reactive power support was part of the system operator's activities and the expenses incurred in providing for such services were included within the electricity tariff charged to customers. In deregulated electricity markets, provision for reactive power support needs to be made by the ISO in order to meet the contracted transactions in a secure manner. Since it is not desirable to transport reactive power over the network, procurement of reactive power services should be done taking into account the perceived demand conditions, mix of the load and availability of reactive power resources. Most often, the independent generators or customers own the resources for reactive support such as synchronous generators, synchronous condensers, capacitor banks, reactors, static var compensators and FACTS devices, and the ISO needs to enter into contracts with them for such provision. From the earlier discussions we see that there has been a move towards creating payment mechanisms for reactive power services in many systems. However, a fully competitive reactive power market has yet to emerge. Several issues make operating reactive power services within a competitive market framework very difficult.

Active and reactive marginal prices are normally obtained through solving the optimal power flow in which an objective function subject to a set of equality and inequality constraints is minimized. The objective function is proposed as the summation of active and reactive power production costs, produced by generators and capacitor banks. The suggested hourly cost function takes the form:

$$Cost = \sum_{i\in\{G\}} C_{pgi}(P_{Gi}) + \sum_{i\in\{G\}} C_{qgi}(Q_{Gi}) + \sum_{i\in\{C\}} C_{Cj}(Q_{Cj}) \qquad (1)$$

where {G} is the generator set; {C} is the capacitor set; $C_{pgi}(P_{Gi})$ is the active power production cost of generator $i$; $C_{qgi}(Q_{Gi})$ is the reactive power production cost of generator $i$; $C_{Cj}(Q_{Cj})$ is the equivalent production cost of capacitor to be explained below; $P_{Gi}$, $Q_{Gi}$ are

the active and reactive power output of the generator on bus $i$; and $Q_{Cj}$ is the reactive power output of capacitor $j$. Cost function of active power used in Eq. (1) is considered as follows:

$$C_{pgi} = a + bP_{Gi} + cP_{Gi}^2 \qquad (2)$$

The reactive power cost of generator, i.e. the second item in Eq.(1), is the so-called opportunity cost [17]. Opportunity cost depends on demand and supply in market, so it is hard to determine its exact value. The capacity of generators is limited by the synchronous generator armature current limit, the field current limit, and the under excitation limits. Because of these limits, the production of reactive power may require a reduction of real power output. Opportunity cost is the lost benefit of this reduction of real power output of the generator. In simplest form opportunity cost can be considered as follows:

$$C_{qgi}(Q_{Gi}) = [C_{gpi}(S_{Gi,\max}) - C_{gpi}(\sqrt{S_{Gi,\max}^2 - Q_{Gi}^2})].k \qquad (3)$$

where $S_{Gi,\max}$ is the nominal apparent power of the generator $i$; $k$ is the profit rate of active power generation, usually between 5 and 10%.

The third item of Eq. (1) represents the equivalent production cost for capital investment return of capacitors, which is expressed as 15 years of their depreciate rate.

$$C_{Cj}(Q_{Cj}) = \frac{investment\ Cost}{Operating\ Hours}.Q_{Cj} = \frac{11600\$}{15\times 365\times 24\times (2/3)}.Q_{Cj} = 0.1324\times Q_{Cj}\ \$/MVAh \qquad (4)$$

where the investment cost of a capacitor is \$11600/MVA, and their average working rate and life span are 2/3 and 15 years, respectively.

Equality and Inequality;The equality and inequality constraints include the load flow equations, active and reactive power output of generators, reactive power output of capacitors, and the bus voltage limits at the normal operating condition.

The equality constraints are load flow equations:

$$P_{Gi} - P_{Di} - \sum |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_{ij}) = 0 \qquad (5)$$

$$Q_{Gi} - Q_{Di} - \sum |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_{ij}) = 0 \qquad (6)$$

$$P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max} \qquad (7)$$

$$Q_{Gi,\min} \le Q_{Gi} \le Q_{Gi,\max} \qquad (8)$$

Reactive power output limit of capacitor:

$$0 \le Q_{Cj} \le Q_{j,\max} \tag{9}$$

Transmission line limit:

$$|P_{ij}| \le P_{ij,\max},\ P_{ij} = |V_i||V_j||V_{ij}|\cos(\theta_{ij} - \delta_{ij}) - |V_i|^2|Y_{ij}|\cos\theta_{ij} \tag{10}$$

and bus voltage limits:

$$V_{i,\min} \le |V_i| \le V_{i,\max} \tag{11}$$

Based on the above mathematical model the corresponding Lagrangian function of this optimization problem takes the form:

(12)

$$\begin{aligned}
L = & \sum_{i\in\{G\}} \left[C_{pgi}(P_{Gi}) + C_{qgi}(Q_{Gi})\right] + \sum_{i\in\{C\}} C_{Cj}(Q_{Cj}) \\
& - \sum_{i\in N} \lambda_{pi}\left[P_{Gi} - P_{Di} - \sum |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_{ij})\right] \\
& - \sum_{i\in} \lambda_{qi}\left[Q_{Gi} - Q_{Di} - \sum |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_{ij})\right] \\
& + \sum_{i\in\{G\}} \mu_{pi,\min}(P_{Gi,\min} - P_{Gi}) \\
& + \sum_{i\in\{G\}} \mu_{pi,\max}(P_{Gi} - P_{Gi,\max}) \\
& + \sum_{i\in\{G\}} \mu_{si}(P_{Gi}^2 + Q_{Gi}^2 - S_{Gi,\max}^2) \\
& + \sum_{j\in\{C\}} \mu_{ci,\min}(Q_{Cj,\min} - Q_{Cj}) \\
& + \sum_{j\in\{C\}} \mu_{ci,\max}(Q_{Cj} - Q_{Cj,\max}) \\
& + \sum_{i\in N} \sum_{\substack{i\in N \\ j\neq i}} \eta_{ij}(S_{ij} - S_{ij,\max}) \\
& + \sum_{i\in N} \nu_{i,\min}(V_{i,\min} - V_i) \\
& + \sum_{i\in N} \nu_{i,\max}(V_i - V_{i,\max})
\end{aligned}$$

According to microeconomics, the marginal prices for active power and reactive power at th bus are kpi and , respectively and are defined as [18]:

$$\lambda_{pi} = \frac{\partial L}{\partial P_{Di}} \tag{13}$$

$$\lambda_{qi} = \frac{\partial L}{\partial Q_{Di}} \tag{14}$$

## Vector Evaluated Particle Swarm Optimization (VEPSO)

Real world applications involve solving problems whose objectives are normally in conflict. There are

many optimization algorithms available to engineers with many methods appropriate only for certain type of problems. Thus, it is important to be able to recognize the characteristics of a problem in order to identify an appropriate solution technique.

Particle swarm optimization (PSO) is one of the powerfull optimization algorithms. PSO was introduced by Kennedy and Eberhart [19,20], inspired by the social behaviour of animals such as bird flocking, fish schooling, and the swarm theory. Compared with other similar evolutionary techniques, PSO has some attractive characteristics and in many a cases proved to be more eff ective [21]. There are numerous methods for solving multiple objective problems using the PSO algorithm [22–26]. One of the most common approaches is to aggregate all the objective functions with appropriate weights into a single comprehensive objective function [22].This necessitates an knowledge of the problem domain, to assign the weights appropriately. The nature of the current problem and the objective being considered render the separate evaluation of these objectives more appropriate. There have been several other recent methodologies proposed for using PSO to handle multiple objective functions.

The multiobjective heuristic VEPSO algorithm, introduced by Parsopoulos and Vrahatis in 2002 [27], uses the multiswarms concept from the vector evaluated genetic algorithm (VEGA) algorithm [28], in which each swarm optimises one objective function by using the best solution from another swarm as a guidance. It is similar to two single objective functions being separately evaluated by separate swarms. In the better word, the main idea behind this algorithm is to "evolve" two independent swarms and exchange information between them. The main features of VEPSO are explained in detail below:

The VEPSO method assumes that $M$ swarms $S_1$, $S_2$,..., $S_M$ each of size $N$ aim to optimize simultaneously $M$ -objective functions. Each swarm is exclusively evaluated according to one of the objective functions. Let $X_i^j(t)$, $V_i^j(t)$, $P_i^j(t)$, $P_{gb}^j(t)$ be the current position, velocity, the best previous position of the *i*th particle and the global best in the *j*th swarm, respectively, at a given time $t$. Each swarm optimises one objective function using the $P_{gb}^j(t)$ from another swarm. Then the VEPSO's swarms should be updated according to the following equations:

$$V_i^j(t+1) = k^j \times [\omega_i^j \times V_i^j(t) + C_p^j \times r_1 \times (P_i^j - S_i^j(t)) + C_g^j \times r_2 \times (P_i^k - S_i^j(t))] \quad (15)$$

$$X_i^j(t+1) = X_i^j(t) + V_i^j(t+1) \quad (16)$$

where, is the cognitive learning rate and is the social learning rate. The factors and are randomly generated within the range , is the inertia factor and parameter can be selected in a number of ways, resulting diff erent information migration schemes between the multiple swarms.

## Simulation Resultes and Discoussion

To investigate the validity of the proposed method, it has been applied to IEEE 5-bus and IEEE-30 bus system shown in Fig. 1 and Fig. 6 respectivelly. In the 5 bus system two generators installed on buses 1 and 2.The nominal apparent power output of each generator is 125 MVA. The lower and upper limits of power generation is 50 and 150 MW. Generators characteristics are given in Table 1. The system loads on buses 2-5 are listed in Table 2 with a common power factor of 0.9. The transmission line impedance and charging admittance are given in Table 3. The other system operation limits are:

- Transmission limit: $|S_{ij}| \leq 1.8^{pu}$ .
- Voltage limit: $0.95^{pu} \leq |V_i| \leq 1.05^{pu}$ .
- Swing bus settings: $V_1 = 1.8^{pu}$ and $\delta_1 = 0$ .

In order to study the impact of reactive power cost factor and investment cost of capacitor bank on the marginal price of reactive power, four cases are studied:

Case 1**:** The objective function is minimization of generator active power production cost. It includes only the first item of (1).

Case 2: The objective function is minimization of generator active power production cost and the opportunity cost of generator real power production. It includes the first and second item of (1). In this case capacitors are not installed.

Case 3: The objective function is minimization of generator active power production cost and the overall capacitor cost. It includes the first and second item of (1).

Case 4: The objective function is minimization of generator active power production cost, the opportunity cost of generator real power production and the overall capacitor cost.

The computer test results from cases 1-4 are used to study the impacts of objective functions on reactive power marginal price under normal operation conditions, where is the average cost of reactive power of the whole network, which is obtained through dividing the total system reactive power cost by the total reactive power demand. The system result shown in Fig.2 to Fig. 5 and listed in Table 4. These figures show the active power marginal prices for case 1 to 4.

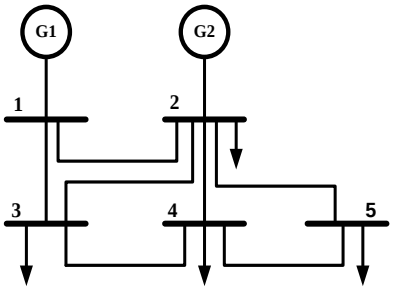



**Fig. 1: IEEE 5-bus test system**

**Table 1: Generators characteristics**

| $P_{min}$ | $P_{max}$ | *c* *($/hour)* | *b* *($/hour)* | *a* *($/hour)* | Generators |
|---|---|---|---|---|---|
| 20 | 125 | 420 | 750 | 75 | *G1* |

| | | | | | |
|---|---|---|---|---|---|
| 20 | 125 | 420 | 750 | 75 | *G2* |

**Table 2: loads characteristics**

| *Q* | *P* | Bus number |
|---|---|---|
| 0.097 | 0.2 | 2 |
| 0.22 | 0.45 | 3 |
| 0.19 | 0.4 | 4 |
| 0.29 | 0.6 | 5 |

**Table 3: Transmission line parameters**

| ***From*** | ***To*** | ***R*** | ***X*** | ***$Y_c/2$*** |
|---|---|---|---|---|
| 1 | 2 | 0.02 | 0.06 | 0.03 |
| 1 | 3 | 0.08 | 0.24 | 0.025 |
| 2 | 3 | 0.06 | 0.18 | 0.02 |
| 2 | 4 | 0.06 | 0.18 | 0.02 |
| 2 | 5 | 0.04 | 0.12 | 0.15 |
| 3 | 4 | 0.01 | 0.03 | 0.01 |
| 4 | 5 | 0.08 | 0.24 | 0.025 |

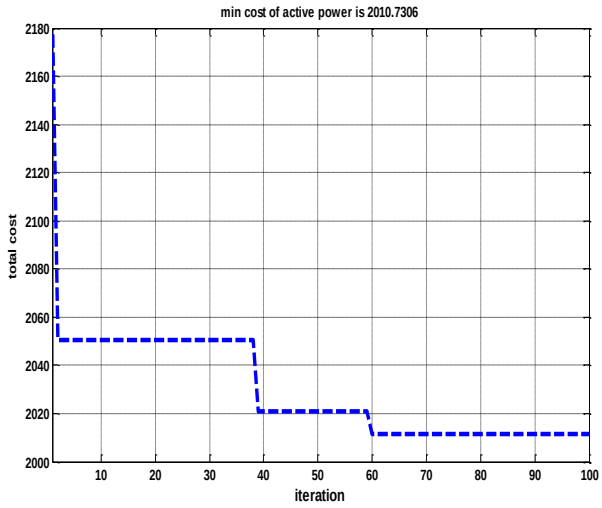



**Fig. 2: Active power production cost of generators (case 1)**

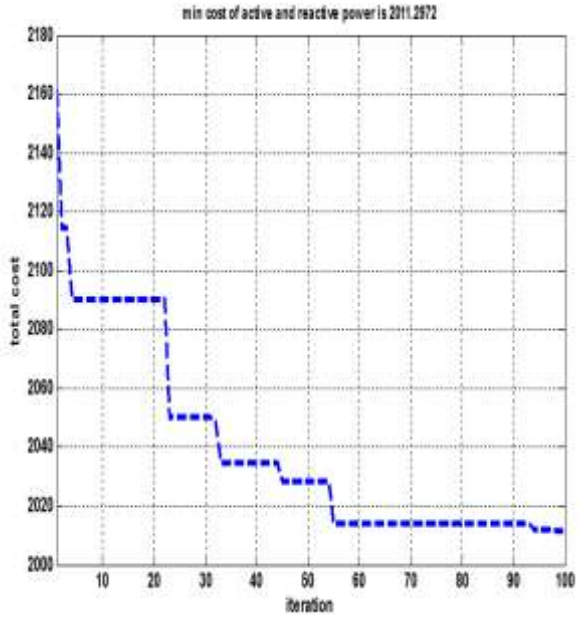



**Fig.3: Active and reactive power production cost of generators (case 2)**

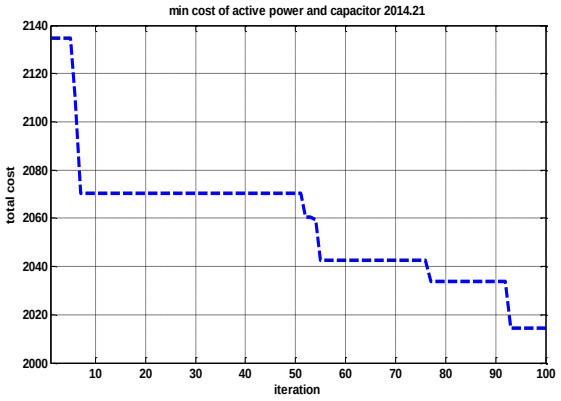



**Fig.4: Active power of generators and reactive power production of capacitor bank cost (case 3)**

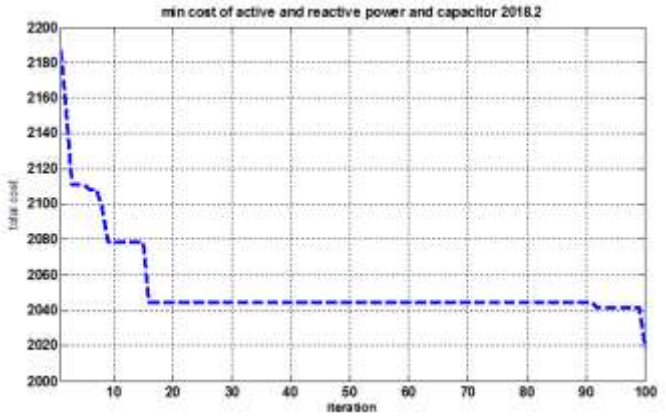



**Fig.5: Active and reactive power production of generators and reactive power production of capacitor bank cost (case 4)**

**Table 4: Test results of cases 1-4 and comparition with GA and Ant colony algorithm [28] *($/hour)***

| **Strategy** | ***Case 1*** | ***Case 2*** | ***Case 3*** | ***Case 4*** |
|---|---|---|---|---|
| Genetic algorithm | 2012.2920 | 2012.8430 | 2016.1620 | 2019.3820 |
| Ant colony search algorithm | 2012.2545 | 2012.8259 | 2016.1554 | 2018.2306 |
| VEPSO algorithm | 2010.7306 | 2011.2972 | 2014.2100 | 2018.2100 |

Fig. 6 depicts the IEEE 30 bus system with 30 bus bars, and 41 links connecting them. Generators characteristics are given in Table 5. In this test system the impact of reactive

A. power cost factor on the marginal price of reactive power in two cases are studied and compared with PSO algorithm.

B. Case 1: The objective function is minimization of generator active power production cost. It includes only the first item of (1).

C. Case 2: The objective function is minimization of generator active power production cost and the opportunity cost of generator real power production. It includes the first and second item of (1).

D. The test results of Matlab simulation are used to study the impacts of objective functions on active and reactive power marginal price in case 1 and 2 under normal operation conditions in IEEE-30 bus standard system. Fig. 7 to Fig. 10 shows the the system results with PSO and VEPSO algorithm and these results listed in Table 5. These results show the good prformance of VEPSO algorithm in optimal power flow and active and reactive power pricing of system.

**Table 4: Generators characteristics of IEEE-30 bus system**

| *Generators* | *a (S/hour)* | *b (S/hour)* | *c (S/hour)* | $P_g$ | $Q_g$ |
|---|---|---|---|---|---|
| $G_1$ | 0.0200 | 2 | 0 | 25/97 | **-12/37** |
| $G_2$ | 0.0175 | 1.75 | 0 | 60/97 | **-13/36** |
| $G_{13}$ | 0.0625 | 1 | 0 | 37/00 | **-0/05** |
| $G_{22}$ | 0.0083 | 3.25 | 0 | 21/59 | **6/08** |
| *$G_{23}$* | *0.025* | *0* | 0 | *19/20* | **-3/28** |
| *$G_{27}$* | *0.025* | *0* | 0 | *26/91* | **-1/87** |

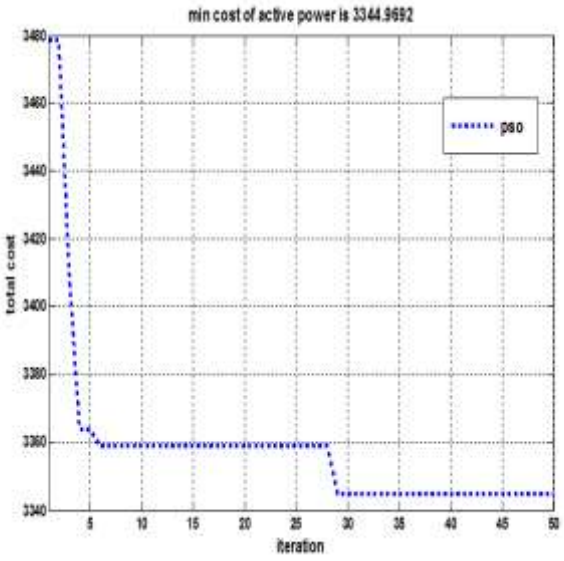



**Fig. 6: Active power production cost of generators for IEEE-30 bus system with PSO algorithm (case 1)**

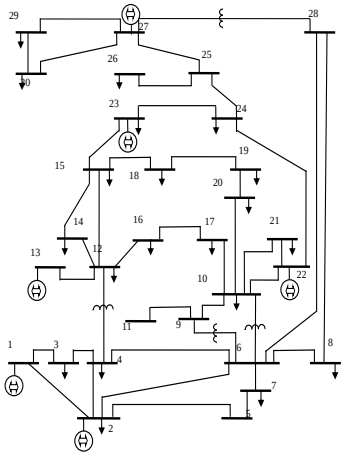


**Fig. 7: IEEE 30-bus test system**

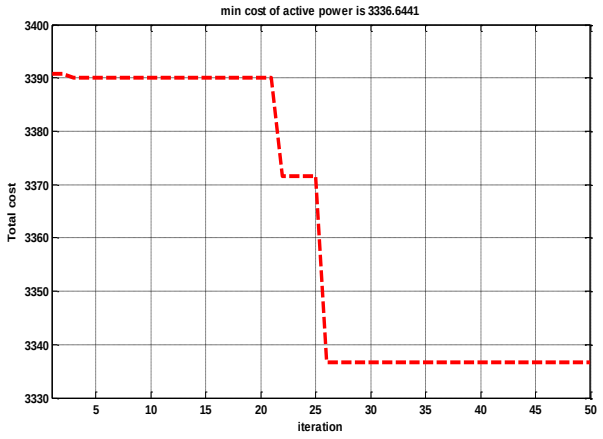



**Fig. 8: Active power production cost of generators for IEEE-30 bus system withVEPSO algorithm (case 1)**

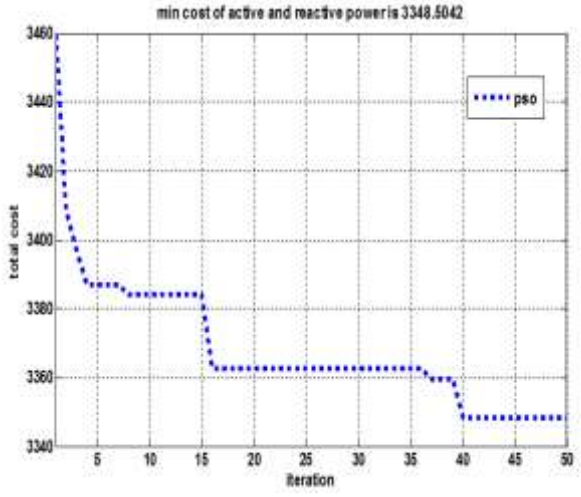



**Fig. 9: Active and reactive power production cost of generators for IEEE-30 bus system with PSO algorithm (case 2)**




***Fig. 10:** ACTIVE AND REACTIVE POWER PRODUCTION COST OF GENERATORS FOR IEEE-30 BUS SYSTEM WITHVEPSO ALGORITHM (CASE 2)*

***TABLE 4:** TEST RESULTS OF CASES 1-4 AND COMPARITION WITH GA AND ANT COLONY ALGORITHM ($/HOUR))*

| Strategy | *Case 1* | *Case 2* |
|---|---|---|
| PSO algorithm | 3344.9692 | 3348.5042 |
| VEPSO algorithm | 3336.6441 | 3338.8218 |

## Conclusion

For decades, power factor penalties have been used as the basis for reactive power pricing. With the restructuring of the electric power industry during the past ecade, operation and control strategies have undergone a shift in paradigm. This paper examines the management of reactive power services in deregulated electricity markets around the world. both active and reactive power production costs of generators and capital cost of capacitors are considered in the objective function of OPF problem in IEEE-5 and IEEE-30 bus standard system by VEPSO algorithm. Test results show that the reactive power production cost and the capital investment of capacitors should be considered in reactive power pricing for their noticeable impacts on reactive power marginal price. The simulation results show that the proposed method based on the VEPSO algorithm is capable of finding global optimum solution for the OPF problem and Simulation results show that effective performance of VEPSO algorithm in optimization of cost objective function of reactive power.

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