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REACTIVE POWER MANAGEMENT IN A DEREGULATED POWER SYSTEM WITH CONSIDERING VOLTAGE STABILITY

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Abstract-- **In this paper an overview of the angle based Particle Swarm Optimization algorithm (θ-PSO) followed by its application to optimal reactive power procurement is provided. Among the ancillary services is the reactive power control, which has an important role in efficient operation of the power systems. Implementing a commercial based structure for reactive power scheduling is the most attractive option in deregulated environments. Here is defined a model which attempts to minimize the cost of reactive power procurement and energy losses which incorporates ordinary technical criteria and voltage stability margin in special as soft constraints. From mathematical points of view, the reactive power market can be formulated as a nonlinear optimization problem. The θ-PSO, as an extension of the standard Particle Swarm Optimization algorithm, is applied to solve the problem of reactive power market. The IEEE 30-bus test system is used to illustrate the efficiency of this approach. The results are compared with those obtained by standard PSO showing that the θ-PSO has a good potential to converge to better feasible solutions with few iteration steps.**

Index Terms— **particle swarm, optimization, reactive power market, voltage stability, OPF.**

I. INTRODUCTION

With the emergence of deregulation in power industry, generation, transmission and distribution have been separated into independent entities. In this new environment, the generation parts as well as distribution ones can be owned and managed by private sectors but the transmission system is the sole part that is preferred to be operated monopoly under the control of the independent system operator (ISO). The ISO carries out its responsibilities in managing each ancillary services to provide system reliability and security. Ancillary services are defined as those activities, which are essential to support the transmission of power while maintaining the reliable operation of the system. These services can be provided through an auction-based mechanism [1,2]. Among these services stand the ones associated with the reactive power, which is used for regulating voltage profiles, minimizing real power losses or increasing the reactive power reserves of some key generators.

Implementing a commercial based structure for reactive power scheduling is the most attractive option in deregulated environments. With in the past decade, different competitive structures have been proposed for reactive power procurement, which can be categorized into two groups. The idea behind the first group is to co-optimize active and reactive power markets simultaneously; however in the second one reactive power market is cleared independent of the electricity market activities. In other words, according to the first approach, The ISO should put an effort to minimize the procurement costs of both active and reactive power generation [3]-[5], while in the second approach, ISO can only minimize the incurred costs of reactive power utilization and hence the real power transactions are usually assumed to be fixed at this stage [6]. The second approach introduces relatively simple model for reactive power market, since it takes the advantages of using active and reactive power decomposition approach into the market model. The model presented in this paper for reactive power procurement belongs to the second category with the aim of minimizing reactive power production costs as well as costs of providing the real power losses.

Generally, the reactive power market is usually formulated as a nonlinear programming (NLP) problem. The problem consists of a cost function with different sorts of equality and inequality constraints. In our problem, the equality constraints refer to the power flow equations and the inequality constraints are the limits on system variables including bus voltages, generators' active and reactive power, lines' power flow and etc. Mathematical based optimization algorithms are very efficient to handle nonlinear convex problems. The prior studies on reactive power and voltage control problems formulation show that the mathematical model usually falls into the non-convex NLP problem.

The performance of the gradient-based optimization approaches in finding the global optima is very sensitive to choice of starting point when they are applied to non-convex optimization problems [7]. This is major deficiency of these techniques. The population based optimization algorithms, which try to find the best solution by searching the solution space randomly, are appropriate for solving non-convex nonlinear optimization problems. A survey on the application of intelligent technique to reactive power/voltage control problem has been presented in [8]. Recently, Kennedy and Eberhart have developed a novel and powerful evolutionary computation technique, called PSO [9]. An extension of this optimization technique is the angle based particle swarm optimization or θ-PSO [10]. In references [11] and [12], the PSO is implemented for a well-known economic dispatch problem. Ref. [13] has presented a two-step procedure for handling voltage stability criteria in reactive power optimization problem. In the first stage, PSO is used to minimize the real power losses. In the second stage, maximum loading parameter of the system is evaluated using CPFLOW

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method [14] for the best-found solution. However θ-PSO has not been applied to reactive power market simulation. The objective function of the market consists of the costs of losses as well as reactive power generation costs. The feasibility of the proposed method is demonstrated and compared with the results of the standard PSO.

II. OVERVIEW OF THE PSO ALGORITHM

Standard algorithm

The standard PSO is described in vector notation as follow [9]:

$$v_i(t+1) = \omega v_i(t) + c_1 r_1(t)(p_i(t) - x_i(t)) + c_2 r_2(t)(p_g(t) - x_i(t)), \tag{1}$$

$$x_i(t+1) = x_i(t) + v_i(t+1), \tag{2}$$

for i=1, 2, …, s. Where s is the swarm size, c1 and c2 the acceleration coefficients, ω the inertia weight, r1(t) and r2(t)~U(0, 1), xi(t) the position of particle i at time t, vi(t) the velocity of particle i at time t, pi(t) the personal best solution of particle i at time t, and pg(t) the global best solution at time t. The particle position xi(t+1) is updated using its current value and the newly computed velocity vi(t+1), which is determined by the values of vi(t), xi(t), pi(t), pg(t) and coefficients ω, c1 and c2.

$\boldsymbol{\theta}$-PSO algorithm

In $\boldsymbol{\theta}$-PSO, the increment of phase angle replaces the increment of velocity and the position is decided by the mapping of the phase angle [10]. $\boldsymbol{\theta}$-PSO can be described in vector notation as follows:

$$\Delta\theta_i(t+1) = \omega\Delta\theta_i(t) + c1r1(t)(\theta ib(t) - \theta i(t)) + c2r2(t)(\theta g(t) - \theta_i(t)), \tag{3}$$

$$\theta_i(t+1) = \theta_i(t) + \Delta\theta_i(t+1), \tag{4}$$

$$xi(t) = f(\theta_i(t)), \tag{5}$$

$$Fi(t) = fitnessvalue(xi(t)), \tag{6}$$

with $\theta_{ij} \in (\theta_{\min}, \theta_{\max})$, $\Delta\theta_{ij} \in (\Delta\theta_{\min}, \Delta\theta_{\max})$, $x_{ij} \in (x_{\min}, x\max)$ and f being a monotonic mapping function, i=1, 2, …, s and j=1, 2, …, n. Where we assume the global optimal particle is not on the boundary; s, c1, c2, ω, r1(t), r2(t), and xi(t) are the same as those in Eqs.(1) and (2); n is the dimension of the problem; θi(t) the phase angle of particle i at time t; Δθi(t) the increment of particle i's phase angle at time t; θib(t) the phase angle of the personal best solution of particle i at time t; θg(t) the phase angle of the global best solution at time t; Fi(t) the fitness value of particle i at time t, which is decided by the function fitnessvalue; Fib(t) the personal best fitness value of particle i at time t; Fg(t) the global best fitness value at time t. In this paper, we set θij∈ (−π/2, π/2), Δθij∈ (−π/2,π/2) and

$$f(\theta_{ij}) = \frac{x_{\max} - x_{\min}}{2}\sin\theta_{ij} + \frac{x_{\max} + x_{\min}}{2}. \tag{7}$$

The $\boldsymbol{\theta}$-PSO algorithm can be summarized as follows:

```
Create and initialize an $n$-dimensional swarm (phase angle $\boldsymbol{\theta}_i(1)$ );
Repeat $t$=1, 2,…, iteration number;
for each particle $i$=1, 2, …, $s$
  if $t$=1
    calculate $\boldsymbol{x}_i(1)$ using Eq.(5);
    calculate the fitness value $F_i(1)$ using Eq.(6);
    $F_{ib}(1)=F_i(1)$; $\boldsymbol{\theta}_{ib}(1)=\boldsymbol{\theta}_i(1)$;
    $F_g(1)=F_i(1)$; $\boldsymbol{\theta}_g(1)=\boldsymbol{\theta}_i(1)$;
  else if $t$>1
      update the increment of the phase angle $\Delta\boldsymbol{\theta}_i(t)$ using
          Eq.(3) and limit $\Delta\boldsymbol{\theta}_i(t)$ to ($\Delta\theta_{\min}$, $\Delta\theta_{\max}$);
      update $\boldsymbol{\theta}_i(t)$ using Eq.(4) and limit $\boldsymbol{\theta}_i(t)$ to ($\theta_{\min}$, $\theta_{\max}$);
      update $\boldsymbol{x}_i(t)$ using Eq.(5);
      update the fitness value $F_i(t)$ using Eq.(6);
      if $F_i(t)<F_{ib}(t)$
        $F_{ib}(t)=F_i(t)$; $\boldsymbol{\theta}_{ib}(t)=\boldsymbol{\theta}_i(t)$;
     end
     if $F_i(t)<F_g(t)$
       $F_g(t)=F_i(t)$; $\boldsymbol{\theta}_g(t)=\boldsymbol{\theta}_i(t)$;
    end
  end
end // until the stopping condition is true
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III. REACTIVE POWER MARKET FORMULATION

Vertically integrated power systems have been designed and operated so that conditions in close proximity to security boundaries are not encountered. In other words, reactive power control objectives concentrate on improving voltage profile and voltage stability requirement as two main purposes, however, in restructured power systems, financial interests introduce new dimension in an open market system, where the cost and contribution of different reactive power facilities should be more precisely evaluated. In general, procurement problem is a nonlinear optimal power flow-programming problem that is used to determine the optimal reactive dispatch to minimize associated costs, subject to certain system constraints. The methodology presented here considers the voltage stability criteria as a soft constraint. Thus, the reactive power market model, which is consider the voltage stability margin can be generally formulated as following:

A. Reactive market objective function

$$Minimize\ f(\underline{Q}_g, \underline{Q}_{sh}) = \sum_{i=1}^{N_g} C_{gqi}(Q_{gi}) + \sum_{i=1}^{N_{sh}} C_{shi}(Q_{shi}) + 0.5.MCP.\sum_{i,j}(G_{i,j} \times (V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j))) \tag{8}$$

Where:

i,j	index for buses;
Q_g	generators VAr output;
N_g	number of generators;
Q_{sh}	static VAr compensators output; ;
N_{sh}	number of static compensators;
V	voltage at bus in per unit;
$G_{i,j}$=real($Y_{i,j}$)	conductance of line i-j;
θ	angle associated with Y bus;
Y	network admittance matrix;
MCP	Market Clearing Price.

The objective function includes total payment of reactive power procurement and payment associated with real power losses of transmission lines. In this model, it is assumed that the slack generator should provide the network real power losses, and it is remunerated according to electricity price or MCP price, which has been settled in electricity market.

B. *Constraints on the power system and resources*

1) Power flow equations at normal condition:

$$P^{\circ}_{gi} - P^{\circ}_{di} = \sum_{j} V_i Y_{i,j} V_j \cos(\theta_{i,j} + \delta_i - \delta_j) \qquad (9)$$

$$Q^{\circ}_{gi} + Q^{\circ}_{shi} - \tan(\varphi^{\circ}_{di}).P^{\circ}_{di} = \sum_{j} V_i Y_{i,j} V_j \sin(\theta_{i,j} + \delta_i - \delta_j) \qquad (10)$$

Where:

P°_{gi} , P°_{di}	denote generation and consumption active powers;
φ°_{di}	denotes power angle of consumption loads.

2) Power flow equations at stressed condition: (12) - (11)

$$(1+vsm)(P^{\circ}_{gi} - P^{\circ}_{di}) = \sum_{j} V_i^{vsm} Y_{i,j} V_j^{vsm} \cos(\theta_{i,j} + \delta_{ij}^{vsm})$$

$$Q^{vsm}_{gi} + Q^{\circ}_{shi} - (1+vsm)\tan(\varphi^{\circ}_{di}).P^{\circ}_{di} = \sum_{j} V_i^{vsm} Y_{i,j} V_j^{vsm} \sin(\theta_{i,j} + \delta_{ij}^{vsm})$$

In above equations, variables indicated by superscript "$\circ$"are used to represent base value of variables while "vsm" in used for stressed condition where all generation and consumption values are increased based on their initial values. This concept is implemented by multiplying of factor (1+vsm) to P_{gi} , P_{di} and Q_{di}.

3) Reactive power-generation limits

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \ ; \ Q_{gi}^{\min} \le Q_{gi}^{vsm} \le Q_{gi}^{\max} \qquad (13)$$

$$Q_{shi}^{\min} \le Q_{shi} \le Q_{shi}^{\max} \ ; \qquad (14)$$

$Q_{gi}^{\max}$ and $Q_{gi}^{\min}$ are the maximum and minimum reactive power that a generator can provide. These values vary with a change in active power output of a generator. Capability curve of a generator is usually used to demonstrate relation between its active and reactive power outputs. A typical capability curve of a generator is shown in Figure.1. It is restricted to maximum stator winding heating limit, which depends on stator current and it is also restricted to maximum field winding heating limit or end region heating limit of rotor when generator operates at over-excitation mode or when generator operates in under-excitation mode. The feasible operating condition of a generator can be expressed as a function of its active and reactive operating current point, its terminal and internal setup voltages and its synchronous reactance [15]. However, this paper assumes that generators are allowed to propose their reactive power generation capability regarding their active power generation points.

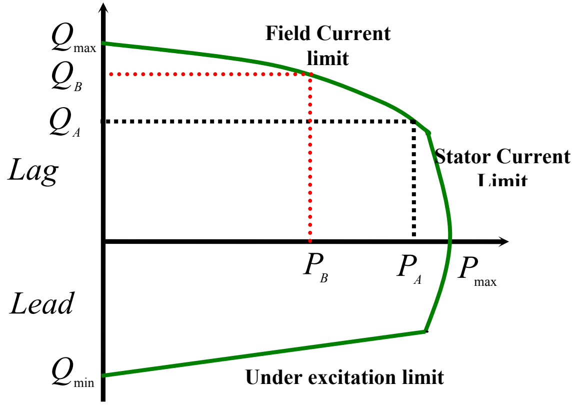

Figure1. Typical capability curve of a generator

4) Bus voltage limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \ ; \ V_i^{\min} \le V_i^{vsm} \le V_i^{\max} \qquad (15)$$

$$V_i^{vsm} = cons. \qquad if \ \ i \in generator\,bus \,;$$

The value of voltage stability margin should be determined in advance by the ISO who is legally responsible for the security and reliability of the power system. In this paper, we do not intend to calculate "vsm" factor, however we have presented a methodology for modeling voltage stability in reactive power market. This method is called fixed voltage stability margin formulation. Other strategies useful to handle voltage stability problem are introduced in [16,17].

C. *Reactive power production costs*

1) Synchronous generators

Active power generation decreases the reactive power capability of a generator as shown in Figure.1. The cost of reactive power production can be modeled using opportunity cost calculation [6]. An approximation for cost of reactive power production corresponding to the first term of (8), is given in the equation (16).

$$C_{gqi}(Q_{gi}) = [C_{gpi}(S_{gi}) - C_{gpi}(\sqrt{S_{gi}^2 - Q_{gi}^2})]K_{gi} \qquad (16)$$

Where:

$C_{gpi}(P_{gi}) = aP_{gi}^2 + bP_{gi} + c$: active power generation cost.

Q_{gi} : reactive power output of i-th generator.

$S_{gi} = \sqrt{P_{gi}^2 + Q_{gi}^2}$: apparent power of i-th generator.

K_{gi} :profit rate of active power, usually between 0.05~0.1.

2) Static VAr Compensators

The second term in (8) is total production cost of static VAr compensators, which can be expressed as following equation for the device installed at bus j.

$$C_{shj}(Q_{shj}) = r_{shj} Q_{shj} \qquad (17)$$

Where:

r_{shj} : is price of reactive power per MVAr and it depends on different factors such as capital investment of compensator, its period of lifetime and average utilization factor. For example, a

SVC with an investment cost of $22000/MVAr, lifetime of 30 year and average use of 2/3, has its r_{cj} as [4,5]:

$$r_{shj} = \frac{22000}{30 \times 365 \times 24 \times \frac{2}{3}} = 0.1225(\$/MVAr) \qquad (18)$$

Q_{shj} : injected reactive power at bus j in MVAr.

IV. Θ-PSO APPLIED TO REACTIVE POWER MARKET

The following procedure can be used for obtaining optimal solution of the proposed reactive power market:

Step1. Initial populations of agents are generated randomly inside the searching space specified by upper and lower bands of control variables. In this problem, control variables consist of output voltage of generators and reactive power outputs of static VAr compensators. Initial velocities are also assigned to each particle. For each agent, P_{best} is initialized with current position.

Step2. For each individual, equations (9) and (10) are evaluated. If the obtained values for state variables satisfy conditions (13) and (15), then go to step 3, otherwise assign a high value to objective function and then go to step 4.

Step3. The control variables are fixed and then equations (11) and (12) are evaluated. if the obtained values for state variables satisfy conditions (13)~(11) go to step 4, otherwise assign a high value to objective function and then go to next step.

Step4. New velocities are calculated using (2).

Step5. New positions are calculated using (3).

Step6. If iteration number reaches the maximum iteration number then stop and print final results, otherwise go to step2.

V. SIMULATION AND RESULTS

In this section, the feasible solution associated with the standard PSO and θ-PSO applied to reactive power market are obtained and compared with each other. To pursue this purpose, reactive power market model is implemented over the IEEE 30-bus test system. Network configuration and transmission lines data are given in [18]. The characteristics of generating units are tabulated in TABLE I.

TABLE I. GENERATING UNIT CHARACTERISTICS

	P_g (MW)	Q_g(MVAr)	V_G	P_{gmax}(MW)
GEN_1	25.97	-12.37	1.00	80
GEN_2	60.97	-13.36	1.00	80
GEN_{13}	37	-0.05	1.00	50
GEN_{22}	21.59	6.08	1.00	50
GEN_{23}	19.2	-3.28	1.00	30
GEN_{27}	26.91	-1.87	1.00	55

The second column in TABLE.I represents reactive power output of generators when they are required to fix output voltage at desired values indicated in column three. In this condition, real power loss of the system is 2.444 MW.

Reactive power costs of generation units are calculated by equation 12, where the associated parameters used in this formula are presented in TABLE II.

TABLE II. COEFFICIENT FACTORS OF EQUATION 12.

	a($/Mw^2)	b($/Mw)	c($)	K_g
GEN_1	0.02	2	0.0	0.1
GEN_2	0.0175	1.75	0.0	0.1
GEN_{13}	0.0625	1	0.0	0.1
GEN_{22}	0.0083	3.25	0.0	0.1
GEN_{23}	0.025	3	0.0	0.1
GEN_{27}	0.025	3	0.0	0.1

Figures 2, 3, and 4 show the capability curves of each generator. It is assumed that these curves are submitted to ISO from each generating units. These curves demonstrate the maximum reactive power that each participant is willing to produce.

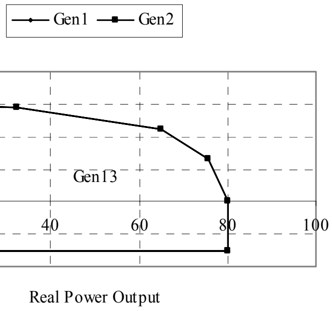

Figure2. Capability curves of generators 1 and 2

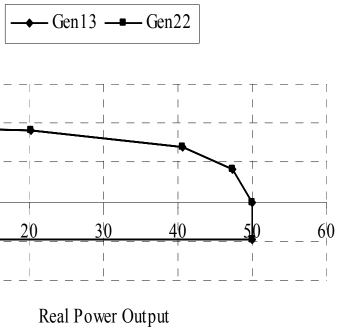

Figure3. Capability curves of generators 13 and 22

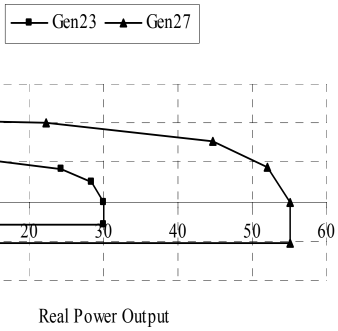

Figure4. Capability curves of generators 23 and 27

Additional energy necessary to provide active power losses is procured from slack generator (G_1) based on electricity market clearing price. In all simulations, MCP is assumed 9.5 $/MW to Figure out the cost of loss. Reactive power prices of electronic-based static VAr compensators are given in TABLE III. These compensators are installed at buses 6, 19, and 28 respectively. Fixed or switched capacitors/inductors cannot be entitled to provide reactive power as an ancillary service, since their reactive power outputs vary with voltage variation.

TABLE III. STATIC COMPENSATORS OPERATING COSTS

	C_6	C_{19}	C_{28}
Cost ($/MVAr)	0.1	0.15	0.07

The voltage stability margin can be improved by efficient reactive power procurement. This is shown on a typical P-V curve of a power system in Figure 5, where consumption loads are fixed. A feasible solution for reactive power is patch may not exist if available reactive power support is not adequate to satisfy the voltage inequality constraints under heavy loading conditions. In this paper, we assume that the voltage stability margin is defined by the ISO, and it can be achieved with the available reactive power resources. This value is assigned to be 0.1 per unit for secure operation of power system in normal operation.

In this case, the optimum reactive power procurement at normal condition is calculated. Thus the optimum point of market is obtained using PSO and *θ*-PSO algorithms and tabulated in TABLE IV. In heuristic methods, the probability of escaping from local minima can increase if the initial population size increases. To provide a rational comparison between the applied methods, similar population size is generated in each algorithm. The number of agents is considered 24. This means that 24 new positions will be explored in every epoch. Doing numerous simulations have indicated that *θ*-PSO algorithm has a good potential for moving particles all over the search space. The results obtained from 100 times execution of different random seeds over reactive power market are summarized in table V that can provide useful information about the performance of each methodology.

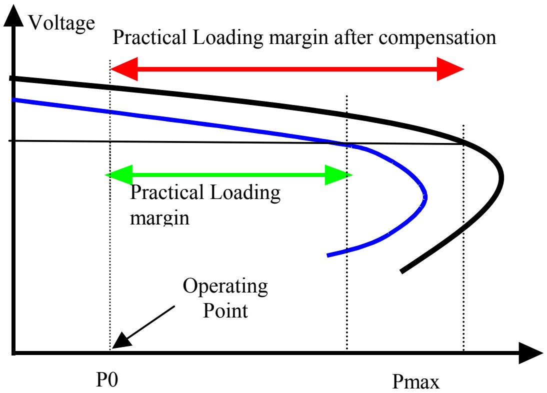

Figure5. Concept of Voltage stability in a power system

TABLE IV. COMPARISON OF SIMULATION RESULTS

P_{loss} =1.9705(MW)	PSO	θ-PSO		PSO	θ-PSO
P_{G1}(MW)	25.5	25.5	Q_{G23}(MVAr)	6.2827	6.268
Q_{G1}(MVAr)	3.4747	3.5247	Q_{G27}(MVAr)	4.3826	4.3474
Q_{G2}(MVAr)	10.694	10.839	Q_{c6}(MVAr)	33.3939	34.0670
Q_{G13}(MVAr)	7.9218	7.8017	Q_{c19}(MVAr)	4.3031	4.1914
Q_{G22}(MVAr)	9.5361	9.4003	Q_{c28}(MVAr)	17.4622	17.0336

TABLE V. STATISTICAL RESULTS OF SIMULATION RESULTS

	The Best Solu.	The Worst Solu.	Mean	Variance
θ-PSO	26.1196	28.1932	26.3442	0.3098
PSO	26.1202	28.3438	26.7753	0.51109

Figure.6 shows typical convergence characteristics for PSO and θ-PSO. It is clear from the figure that PSO is converged to high quality solutions at the early iterations while in standard PSO, the value of objective function changes slightly over iteration.

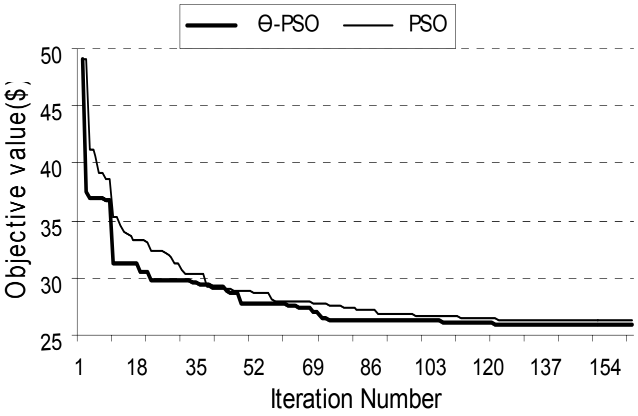

Figure6. Dynamic behaviour of θ-PSO, PSO

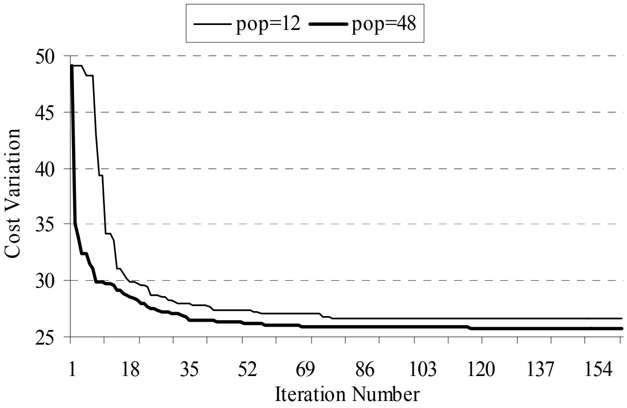

Figure7 Convergence characteristic of θ-PSO for different number of particles.

The impact of population size created in searching space is investigated and the obtained results are shown in Figure7.

This study indicates θ-PSO presents better solution for earlier iteration if the number of individuals increases, however all population size can converge near to optimal value.

VI. CONCLUSION

In this paper, we have firstly presented an angle-based PSO, which increase the speed and accuracy of the standard PSO, and then have successfully implemented the present method for optimal procurement of reactive power in an open electricity market. In the proposed reactive market structure, voltage stability constraint is implemented as a soft constraint to guarantee the security of the system due to some happening in power system such as sudden load perturbation. Thus reactive power management becomes a NLP problem with non-linearity in both objective and its associated constraints. Simulation results carried out for the IEEE 30 bus system, demonstrate excellent capability of θ-PSO in obtaining the best solution as well as converging time when it is compared with the standard PSO algorithm.

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