IEEE International Conference on Intelligent
System Applications to Power Systems (ISAP'99),
Rio de Janeiro, April 4-8, 1999

A PARTICLE SWARM OPTIMIZATION FOR REACTIVE POWER AND VOLTAGE CONTROL CONSIDERING VOLTAGE STABILITY

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Abstract: This paper presents a particle swarm optimization for reactive power and voltage control considering voltage stability. The proposed method determines a control strategy with continuous and discrete control variables such as AVR operating values, OLTC tap positions, and the amount of reactive power compensation equipment. The method also considers voltage stability using a continuation power flow technique. The feasibility of the proposed method is demonstrated on model power systems with promising results.

Key words: Particle Swarm Optimization, Reactive Power and Voltage Control,
Mixed Integer Nonlinear Optimization Problem, Continuation Power Flow

1. INTRODUCTION

Reactive power and voltage Control (Volt/Var Control: VVC) determines an on-line control strategy for keeping voltages of target power systems considering varying loads in each load point and reactive power balance in target power systems. Conventionally, VVC is usually realized based on power flow sensitivity analysis of the operation point considering execution time and available data from the actual target power system. Recently, voltage stability problem has been dominating and the consideration of the stability has been required in VVC problem [1-2]. Since fast computation of voltage stability is required for VVC, continuation power flow (CPFLOW)[3] is suitable for the calculation. The authors has been developed a practical CPFLOW and verified it with an actual power system [4].

VVC can be formulated as a mixed-integer nonlinear optimization problem with continuous state variables such as AVR operating values and discrete state variables such as OLTC tap positions and the amount of reactive power compensation equipment. The objective function can be varied according to the power system condition. For example, the function can be loss minimization of the target power system for the normal operating condition. Conventionally, the methods for VVC problem have been developed using various methods such as fuzzy, expert system, mathematical programming, and sensitivity analysis [5-10]. However, a practical method for a VVC problem formulated as a mixed-integer nonlinear optimization problem has been eagerly awaited.

Particle swarm optimization (PSO) is one of the evolutionary computation (EC) techniques [11]. The original method is able to handle continuous state variables easily and search a solution in a solution space efficiently. However, the method can be expanded to treat both continuous and discrete variables. Therefore, the method can be applicable to a VVC problem.

This paper presents a PSO for a VVC problem formulated as a mixed integer nonlinear optimization problem considering voltage stability. Voltage stability is considered using a continuation power flow. The feasibility of the proposed method for VVC is demonstrated on a simple power system and IEEE 14 bus system with promising results.

2. PROBLEM FORMULATION OF VVC

VVC for a normal power system condition can be formulated as follows:

$$\text{minimize} \quad f_c = \sum_{i=1}^{n} Loss_i \tag{1}$$

where, n : the number of branches,
$Loss_i$: power loss at branch i,

subject to

(1) Voltage constraint
Voltage magnitude at each node must lie within their permissible ranges to maintain power quality.

(2) Power flow constraint
Power flow of each branch must lie within their permissible ranges.

(3) Voltage stability
The Determined VVC strategy should keep voltage stability of the target power system.

Total power loss (P_{loss}) of the target power system is calculated for a certain VVC strategy using load flow calculation. Voltage and power flow constraints can be checked at the load flow calculation and penalty values should be added if the constraints are violated. P-V curve for the determined VVC strategy can be generated and checked whether the VVC is able to keep predetermined MW values or not.

3. OVERVIEW OF PARTICLE SWARM OPTIMIZATION [11]

Particle Swarm Optimization is one of the evolutionary computation techniques. The method has been developed through simulation of simplified social models. The features of the method are as follows:

(1) The method is based on researches on swarms such as fish schooling and bird flocking.
(2) It is based on a simple concept. Therefore, the computation time is short and it requires little memory.
(3) It was originally developed for nonlinear optimization problems with continuous variables. However, it is easily expanded to treat problems with discrete variables. Therefore, it is applicable to mixed integer nonlinear optimization problems with both continuous and discrete variables such as VVC.

The above (3) feature is suitable for VVC problem because practically efficient methods have not been developed for nonlinear problems with both continuous and discrete variables. The above features allow PSO to handle the VVC problem and require few computation time.

According to the research results for bird flocking, birds find food by flocking (not by each individual). It leads to the assumption that information is shared in flocking. According to observation of behavior of human groups, behavior of each individual (agent) is also based on behavior patterns authorized by the groups such as customs and other behavior patterns according to the experiences by each individual. The assumption is a basic concept of PSO. PSO is basically developed through simulation of bird flocking in two dimension space. The position of each agent is represented by XY-axis position and the velocity is expressed by vx (the velocity of X-axis) and vy (the velocity of Y-axis). Modification of the agent position is realized by the position and velocity information.

PSO procedures based on the above concept can be described as follows. Namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value in the group (gbest) among pbests. Each agent tries to modify its position using the current velocity and the distance from pbest and gbest. The modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation.

$$v_i = v_i + rand \times (pbest_i - s_i) + rand \times (gbest - s_i) \qquad (2)$$

where, v_i : velocity of agent i,
rand : uniformly distributed random number between 0 and 1,
s_i : current position of agent i,
$pbest_i$: pbest of agent i,
gbest : gbest of the group.

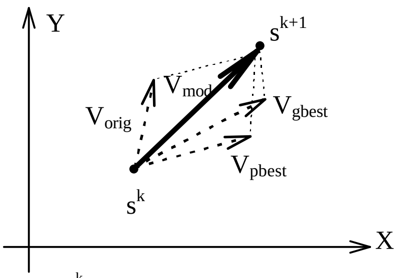
Using the above equation, a certain velocity that gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation.

$$s_i = s_i + v_i \qquad (3)$$

Fig. 1 shows the above concept of modification of searching points.

PSO utilizes several searching points like Genetic Algorithm (GA) and the searching points gradually get close to the global optimal point using its pbest and gbest. The features of the searching procedure can be summarized as follows:

(1) Initial positions of pbest and gbest are different. However, using the different direction of pbest and gbest, all agents gradually get close to the global optimum.
(2) The modified value of the agent position is continuous and the method can be applied to the continuous problem. However, the method can be applied to the discrete problem using grids for XY position and its velocity.
(3) There are no inconsistency in searching procedures even if continuous and discrete state variables are



S^k : current position,
s^{k+1} : modified position,
V_{orig} : current velocity,
V_{mod} : modified velocity,
V_{pbest} : velocity based on pbest
V_{gbest} : velocity based on gbest

Fig.1 Concept of modification of a searching point.

utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer nonlinear optimization problems with continuous and discrete state variables naturally and easily.

(4) The above concept is explained using only XY axis (2 dimensional space). However, the method can be easily applied to n dimensional problem.

The original PSO has been applied to a learning problem of neural networks and Schaffer f6, the famous benchmark function for genetic algorithms and efficiency of the method has been confirmed [11].

4. OVERVIEW OF CONTINUATION POWER FLOW

Continuation power flow (CPFLOW) utilizes power system loads as parameters and calculates a P-V curve by modification of the parameters using the continuation method. The continuation method is one of the methods in applied mathematics and it calculates transition of equilibrium points (for example, P-V curve) by modification of parameters. In order to avoid the ill condition around the nose point, arclength along the P-V curve is introduced as an additional state variable and the power flow equation is expanded. The continuation method is applied to the expanded power flow equation and the P-V curve can be generated rapidly without ill condition around the nose point. CPFLOW can generate a P-V curve automatically and can be applied to large-scale power systems easily [3][4].

The proposed method generates a P-V curve using the CPFLOW technique and calculates a MW margin for the determined control strategy. Then, the method checks whether the MW margin is enough or not compared with the predetermined value. Using the procedure, the method checks whether the target power system can keep voltage stability by the control or not.

5. FORMULATION OF VVC USING PSO

5.1 State Variables

The following control equipment is considered in the VVC problem.

(1) AVR operating values (*continuous* value)

(2) OLTC tap position (*discrete* value)

(3) The amount of reactive power compensation equipment (*discrete* value)

The above state variables are treated in load flow calculation as follows: AVR operating values are treated as voltage specification values. OLTC tap positions are treated as tap ratio to each tap position. The amount of reactive power compensation equipment is treated as corresponding susceptance values.

Each variables are treated in PSO as follows. Initial AVR operating values are generated randomly between upper and lower bounds. The value is also modified in the search procedure between the bounds. OLTC tap position is initially generated randomly between the minimum and maximum tap positions. The value is modified in the search procedure among existing tap positions. The amount of reactive power compensation equipment is also generated from 0 to the number of existing equipment at the substation initially. The value is also modified in the search procedure between 0 and the number of existing equipment.

5.2 VVC algorithm using PSO

The proposed VVC algorithm using PSO is expressed as follows:

Step 1. Initial Searching points (agents) and velocities are generated using the above-mentioned state variables randomly.

Step 2. P_{loss} to the searching point for each agent is calculated using load flow. If the constraints are violated, penalty is added to the loss (evaluation value of agent).

Step 3. Pbest is set to each initial searching point. The initial best evaluated value (loss with penalty) among pbests is set to gbest.

Step 4. Velocities are calculated using (2).

Step 5. New searching points are calculated using (3).

Step 6. P_{loss} to the new searching point and the evaluation value is calculated.

Step 7. If the evaluation value of each agent is better than the previous pbest, the value is set to pbest. If the best pbest is better than gbest, the value is set to gbest. All of gbests are stored as candidates for the final control strategy.

Step 8. If the iteration number reaches to the maximum iteration number, then exit. Otherwise, go to Step 4.

Step 9. The P-V curve is generated for the best gbest among the stored gbests (candidates). If the MW margin is larger than the predetermined value, the control is determined as the final solution. Otherwise, select next gbest and repeat the procedure.

6. NUMERICAL EXAMPLES

6.1 A simple 5 bus system

(1) Simulation conditions

The proposed VVC method is applied to a simple system shown in Fig. 2. Control variables are voltage specification of node 2, and the number of SC in node 3 and 4 (bold italic letters in the figure). The number of agents is 10 in the simulation.

(2) Simulation results

The model system in Fig. 2 is a radial network with one line and two power sources exist on the both ends of the network. Therefore, line flow between node 3 and 4 is minimized in the optimal control. The followings are two local minima in the example.

(1) Voltage spec. on node 1 is 0.805 [pu]
The number of SC on node 3 is 3
The number of SC on node 4 is 2
P_{loss} is 0.011439 [pu]

(2) Voltage spec. on node 1 is 1.1308 [pu]
The number of SC on node 3 is 2
The number of SC on node 4 is 1
P_{loss} is 0.005518 [pu]

The second one (global optimal solution) is generated as the gbest in 27th iteration and all of the agents are converged to the global optimal solution in 44th iteration. P-V curve is generated for the optimal control. In the simulation, the control strategy is checked whether the MW margin above the predetermined voltage level (0.95 [pu]) is enough or not. It keeps the MW margin larger than the predetermined value and it is assured to keep voltage stability.

6.2 A modified IEEE 14 bus system

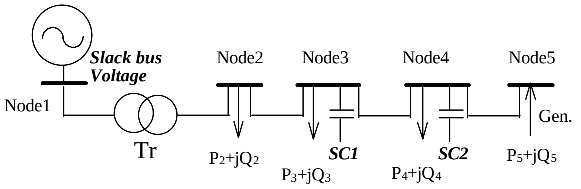


Fig.2 A simple 5 bus system.

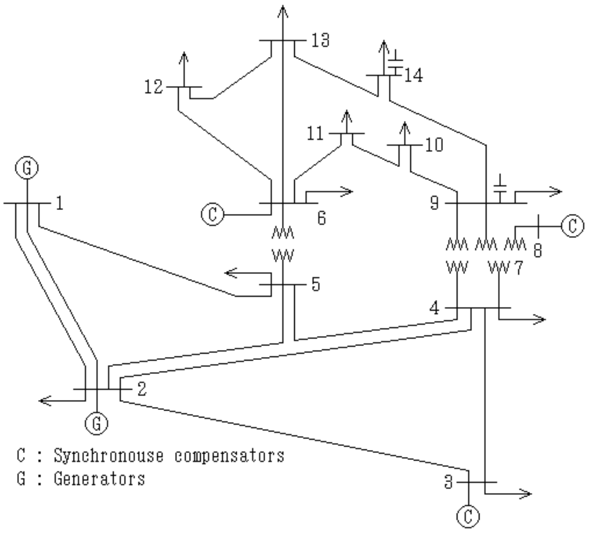


Fig. 3 A modified IEEE 14 bus system.

(1) Simulation conditions

Fig. 3 shows a modified IEEE 14 bus system. Table 1 shows operating conditions of the system. The followings are control variables.

(1) Continuous AVR operating values of node 2,3,6, and 8. Upper and lower bounds are 0.9 and 1.1 [pu].
(2) Discrete tap position of transformers between node 4 and 7, 4 and 9, and 5-6. They are assumed to have 20 tap positions.
(3) Discrete number of installed SC in node 9 and 14. Each node is assumed to have three 0.06 [pu] SC.

The proposed method generates an optimal control for the operating condition. P_{loss} of the original system is 0.1349 [pu]. The number of agents is 10 in the simulation.

(2) Simulation results

Table 2 shows the results by the proposed method and the enumeration method. AVR operating values are discretized with 0.01 [pu] interval for the enumeration method. Therefore, the best result by the enumeration method means the global optimal solution in discretized manner. The results reveal that the proposed method at least generates a solution very near the global optimal solution.

Fig. 4 shows a typical convergence characteristic (transition of P_{loss} of gbest). It is clear from the figure that the solution is converged to a high quality solution at the early iterations (about 50 iteration). The calculation time is about 8 [sec] in 200 iterations using PC (Pentium 400MHz, FreeBSD ver. 3.0, GCC).

The proposed method generates a P-V curve for the optimal control strategy using the continuation

Table 1 System parameters of IEEE 14 bus system.

Bus No.	Vol. [pu]	Node specification		SC [pu]
		P [pu]	Q [pu]	
1^{*1}	1.06	-	-	0.0
2^{*2}	1.045	-0.183	0.127	0.0
3^{*2}	1.010	0.942	0.190	0.0
4		0.478	-0.039	0.0
5		0.076	0.016	0.0
6^{*2}	1.070	0.112	0.075	0.0
7		0.000	0.000	0.0
8^{*2}	1.090	0.000	0.000	0.0
9		0.295	0.166	0.18^{*3}
10		0.090	0.058	0.0
11		0.035	0.018	0.0
12		0.061	0.016	0.0
13		0.135	0.058	0.0
14		0.149	0.050	0.18^{*3}

*1 : Node 1 is slack
*2 : PV spec. node
*3 : 0.06 [pu] * 3 SC

power flow technique. It is verified that the strategy can keep voltage stability. Fig 5 shows an example of P-V curve for node 12 with the optimal control strategy.

7. CONCLUSIONS

This paper presents a particle swarm optimization for reactive power and voltage control (VVC) considering voltage stability. The proposed method formulates VVC problem as a mixed integer nonlinear optimization problem and determines control strategy with continuous and discrete control variables such as AVR operating values, OLTC tap positions, and the amount of reactive power compensation equipment. The method also considers voltage stability using a continuation power flow technique. The feasibility of the proposed method for VVC is demonstrated on simple power systems with promising results.

Application of PSO to power systems is still in early stage. Therefore, it should be investigated the method to find appropriate agent number and initial agent positions. Moreover, the following features are required for the practical VVC.

(1) Reduction of P_{loss} of the target system
(2) Avoidance of operation concentration to a specific equipment
(3) Tracking to load change
(4) Look-ahead control using load forecast
(5) Coordination of control for various equipment
(6) Consideration of voltage stability

For the future works, considering the above VVC features, the proposed method will be improved and applied to practical power systems with comparison using other evolutionary computation techniques.

Table 2 Optimal control for IEEE 14 bus system

Method Cont. Variables	Proposed Method	enumeration method (best)	enumeration method (second best)
AVR 2	1.0464	1.05	1.05
AVR 3	1.0168	1.02	1.02
AVR 6	1.1000	1.10	1.10
AVR 8	1.0977	1.10	1.09
Tap 4-7	0.95	0.95	0.95
Tap 4-9	0.92	0.92	0.92
Tap 5-6	0.97	0.97	0.97
SC 9	0.18	0.18	0.18
SC 14	0.06	0.06	0.06
Loss	0.1323	0.1324	0.1324

AVR 2 : AVR operating values [pu] at node 2
Tap 4 - 7 : Tap ratio between node 4 and 7
SC 9 : Susceptance [pu] at node 9
Loss : power loss [pu]

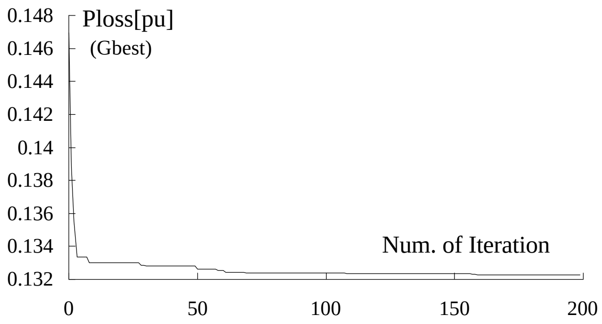


Fig.4 A typical convergence characteristic.

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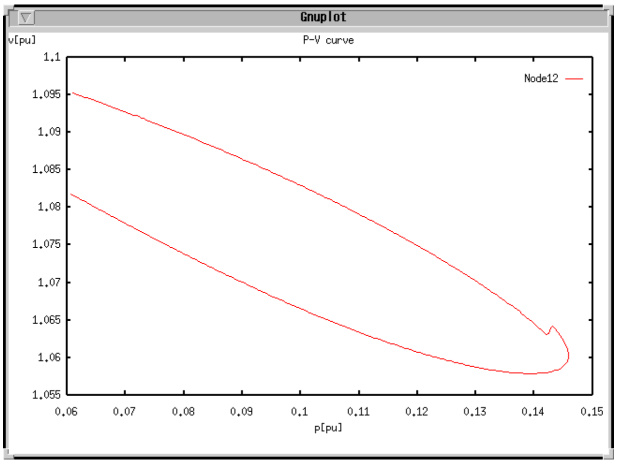

Fig. 5 A P-V curve for the optimal control (Node 12)

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