IEEE Trans. on Power Systems, Vol.15, No.4, pp.1232-1239, November 2001, presented at IEEE PES Winter Meeting, Columbus, Jan.28-Feb.1, 2001

A PARTICLE SWARM OPTIMIZATION FOR REACTIVE POWER AND VOLTAGE CONTROL CONSIDERING VOLTAGE SECURITY ASSESSMENT

Hirotaka Yoshida
Kenichi Kawata
Technical Research Center,
The Kansai Electric Power Co., Inc.
3-11-20, Nakoji, Amagasaki, Hyogo, 661 Japan

Yoshikazu Fukuyama, member, IEEE
Shinichi Takayama, Yosuke Nakanishi, member, IEEE
Power Technology Lab.
Fuji Electric Corporate R & D , Ltd.
No. 1, Fuji-machi, Hino-city, Tokyo,191-8502 Japan

Abstract: This paper presents a particle swarm optimization (PSO) for reactive power and voltage control (Volt/Var Control: VVC) considering voltage security assessment (VSA). VVC can be formulated as a mixed-integer nonlinear optimization problem (MINLP). The proposed method expands the original PSO to handle a MINLP and determines an on-line VVC strategy with continuous and discrete control variables such as automatic voltage regulator (AVR) operating values of generators, tap positions of on-load tap changer (OLTC) of transformers, and the number of reactive power compensation equipment. The method considers voltage security using a continuation power flow and a contingency analysis technique. The feasibility of the proposed method is demonstrated and compared with reactive tabu search (RTS) and the enumeration method on practical power system models with promising results.

Key words: Particle Swarm Optimization, Evolutionary Computation, Reactive Power and Voltage Control, Mixed-Integer Nonlinear Optimization Problem, Voltage Security Assessment, Continuation Power Flow

I. INTRODUCTION

One of the important operating tasks of power utilities is to keep voltage within an allowable range for high quality customer services. Electric power loads vary from hour to hour and voltage can be varied by change of the power load. Power utility operators in control centers handle various equipment such as generators, transformers, static condenser (SC), and shunt reactor (ShR), so that they can inject reactive power and control voltage directly in target power systems in order to follow the load change. VVC determines an on-line control strategy for keeping voltage of target power systems considering the load change and reactive power balance in target power systems.

Current practical VVC in control centers is often realized based on power flow sensitivity analysis of the operation point using limited execution time and available data from the actual target power system. Reduction of power generation cost is one of the current interested issues of power utilities. Therefore, an optimal control to minimize power transmission loss is required for VVC instead of simple power flow sensitivity analysis. Since many voltage collapse accidents have been occurred over the last three decades [1], voltage security problems have been dominated and the consideration of the problem has been required in VVC problem [2,3]. Two evaluations should be performed to consider voltage security. First one is to calculate the distance between the current operating point and the voltage collapse point. The calculation can be realized by drawing a P-V curve using the continuation power flow (CPFLOW) technique [4]. The authors has been developed a practical CPFLOW and verified it with practical power systems [5]. Another one is to suppose various faults for the current operating point in the target power system and calculate the distance between the post-fault operating points and voltage collapse points for each contingency. The calculation is called voltage contingency analysis [1]. If a sufficient distance can be kept for both calculations, the new operating condition calculated by VVC can be evaluated as a secure one. Thus, the advanced VVC requires optimal control strategy considering power loss minimization and voltage security.

VVC can be formulated as a MINLP with continuous state variables such as AVR operating values and discrete state variables such as OLTC tap positions and the number of reactive power compensation equipment such as SC and ShR. The objective function can be varied according to the power system condition. For example, the function can be minimization of power transmission loss of the target power system for the normal operating condition as described above. Conventionally, the methods for VVC problem have been developed using various methods such as fuzzy, expert system, mathematical programming, and sensitivity analysis [6-11]. However, a practical method for a VVC problem formulated as a MINLP with continuous and discrete state variables has been eagerly awaited.

PSO is one of the evolutionary computation (EC) techniques [12]. The method is improved and applied to various problems [13-16]. The original method is able to handle continuous state variables easily. Moreover, the method can be expanded to handle both continuous and discrete variables easily. Therefore, the method can be applicable to VVC formulated as a MINLP. Various methods have been developed for a MINLP such as generalized benders decomposition (GBD) [17] and OA/ER [18]. Using the conventional methods, whole problem is usually divided to sub-problems and various methods are utilized for solving each sub-problem. On the contrary, PSO can handle the whole MINLP easily and naturally and it is easy to apply to various problems compared with the conventional methods. Moreover, VVC requires various constraints that are difficult to be handled by mathematical ways. PSO is expected to be suitable for VVC because it can handle such constraints easily.

This paper presents a PSO for VVC formulated as a MINLP considering VSA. Voltage security assessment is considered using a CPFLOW technique and a fast voltage contingency selection method. The feasibility of the proposed method for VVC is demonstrated and compared with RTS [19][20] and the enumeration method on practical system models with promising results.

II. PROBLEM FORMULATION OF VVC

Problem Formulation

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

$$\text{minimize } f_c(x, y) = \sum_{i=1}^{n} Loss_i \qquad (1)$$

where, n: the number of branches,
x: continuous variables,
y: discrete variables,
$Loss_i$: power loss (ploss) at branch i,

subject to

(a) Voltage constraint
Voltage magnitude at each node must lie within its permissible range to maintain power quality.
(b) Power flow constraint
Power flow of each branch must lie within its permissible range.
(c) Voltage security
The Determined VVC strategy should keep voltage security of the target power system.

Ploss of the target power system is calculated for a certain VVC strategy using load flow calculation with both continuous variables (AVR operating values) and discrete variables (OLTC tap positions and the number of reactive power compensation equipment). Voltage and power flow constraints can be checked at the load flow calculation and penalty values are added if the constraints are violated.

P-V curves for the determined VVC strategy and various contingencies are generated and checked whether the VVC candidate can keep sufficient voltage security margins. The constant power load model is used because the load model is the severest to the voltage security problem. However, if a more complicated load model is required, the proposed method can be easily expanded using a ZIP load model [21].

State Variables

The following control equipment is considered in the VVC problem.

(a) AVR operating values (*continuous variable*)
(b) OLTC tap position (*discrete variable*)
(c) The number of reactive power compensation equipment (*discrete variable*)

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 number of reactive power compensation equipment is treated as corresponding susceptance values.

III. OVERVIEW OF PARTICLE SWARM OPTIMIZATION [12][13]

PSO has been developed through simulation of simplified social models. The features of the method are as follows:

(a) The method is based on researches about swarms such as fish schooling and a flock of birds.
(b) It is based on a simple concept. Therefore, the computation time is short and it requires few memories.
(c) 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 a MINLP with both continuous and discrete variables such as VVC.

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

According to the research results for a flock of birds, birds find food by flocking (not by each individual). The observation leads the assumption that every information is shared inside flocking. Moreover, 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 a flock of birds in two-dimension space. The position of each agent is represented by XY-axis position and the velocity (displacement vector) is expressed by vx (the velocity of X-axis) and vy (the velocity of Y-axis). Modification of the agent position is realized by using the position and the velocity information.

Searching procedures by PSO based on the above concept can be described as follows: a flock of agents 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, namely the best value so far of the group. The modified velocity of each agent can be calculated using the current velocity and the distance from pbest and gbest as shown below:

$$v_i^{k+1} = w_i v_i^k + c_1 rand \times (pbest_i - s_i^k) + c_2 rand \times (gbest - s_i^k) \quad (2)$$

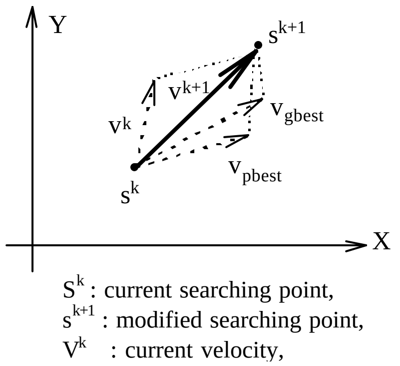
where,

- v_i^k : current velocity of agent i at iteration k,
- v_i^{k+1} : modified velocity of agent i,
- rand : random number between 0 and 1,
- s_i^k : current position of agent i at iteration k,
- $pbest_i$: pbest of agent i,
- gbest : gbest of the group,
- w_i : weight function for velocity of agent i,
- c_i : weight coefficients for each term.

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

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (3)$$

Fig. 1 shows the above concept of modification of searching points. Discrete variables can be handled in (2) and (3) with little modification. Discrete numbers can be used to express the current position and velocity. If a discrete random number is used in (2) and the whole calculation of right-hand side (RHS) of (2) is discretized to the existing discrete number, both continuous and discrete number can be handled in the algorithm with no inconsistency.



S^k : current searching point,
s^{k+1} : modified searching point,
V^k : current velocity,
V^{k+1} : modified velocity,
V_{pbest} : velocity based on pbest
V_{gbest} :velocity based on gbest

Fig.1 Concept of modification of a searching point.

The features of the searching procedure can be summarized as follows:

(a) PSO utilizes several searching points like genetic algorithm (GA) and the searching points gradually get close to the optimal point using their pbests and the gbest.
(b) The first term of RHS of (2) is corresponding to diversification in the search procedure. The second and third terms of that are corresponding to intensification in the search procedure. Namely, the method has a well-balanced mechanism to utilize diversification and intensification in the search procedure efficiently.
(c) The original PSO can be applied to the only continuous problem. However, the method can be expanded to the discrete problem using discrete numbers like grids for XY position and its velocity easily.
(d) There is no inconsistency in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to a MINLP with continuous and discrete state variables naturally and easily.
(e) The above concept is explained using only XY-axis (two-dimension space). However, the method can be easily applied to n-dimension problem.

The above feature (b) can be explained as follows [13]. The RHS of (2) consists of three terms. The first term is the previous velocity of the agent. The second and third terms are utilized to change the velocity of the agent. Without the second and third terms, the agent will keep on “flying” in the same direction until it hits the boundary. Namely, it tries to explore new areas and, therefore, the first term is corresponding to diversification in the search procedure. On the other hand, without the first term, the velocity of the “flying” agent is only determined by using its current position and its best positions in history. Namely, the agents will try to converge to the their pbests and/or gbest and, therefore, the terms are corresponding to intensification in the search procedure. The concept of expanded PSO for MINLP is shown in fig. 2. The original PSO has been applied to a learning problem of neural networks and Schaffer f6, the

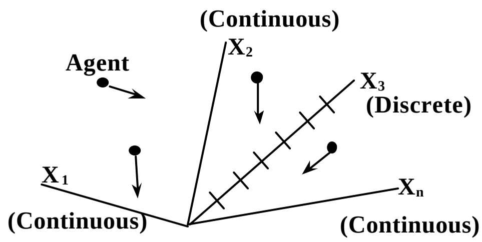


Fig. 2 Concept of expanded PSO for MINLP.

famous benchmark function for GA, and efficiency of the method has been confirmed [12].

IV. VOLTAGE SECURITY ASSESSMENT

The static P-V curve represents the relation between load increase and voltage drop. Namely, the P-V curve can be calculated by increasing total loads in the target power system gradually and plotting the dropped voltage. CPFLOW utilizes power system loads as parameters and calculates the P-V curve by modification of the parameters using a continuation method. The continuation method is one of the methods in applied mathematics and it calculates transition of equilibrium points (e.g. P-V curve) by modification of parameters. In order to avoid the ill-condition around the saddle node bifurcation point (nose point), an 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 [4][5].

The proposed method generates a P-V curve using the CPFLOW technique and calculates a MW margin, distance between the current operating point and the nose point, for the determined control strategy. The proposed method also utilizes the fast voltage contingency analysis method using CPFLOW [22]. Then, the method checks whether the MW margin is enough or not compared with the predetermined value. The procedure for voltage security assessment can be expressed as follows:

Step. 1 Evaluation of the control strategy
It is checked whether the new power system condition after applying the current control strategy has an enough MW margin or not.

Step. 2 Evaluation of various contingencies
The several severe contingencies for the new power system condition after applying the current control strategy are selected by the fast voltage contingency analysis method. The MW margin for the only severe contingencies are calculated using CPFLOW.

If the MW margins for the current control strategy and the severe contingencies are large enough, the current control strategy is selected. Otherwise it is not selected. Using the procedure, the method checks whether the target power system can keep voltage security by the control or not.

VSA consists of static and dynamic VSA and the proposed method only considers the static VSA because of the limited calculation time for on-line VVC. If the dynamic VSA is still required, the VSA used in the proposed method can be replaced with a dynamic VSA tool such as QSS described in [1]. However, in such a case, we have to face the problem of execution time and we may have to develop a parallel computation method for the VSA based on distributed memory tools such as PVM [23] and MPI [24] or shared memory tools such as OpenMP [25].

V. FORMULATION OF VVC USING PSO

Treatment of State Variables

Each variable is treated in PSO as follows: Initial AVR operating values are generated randomly between upper and lower bounds of the voltage specification values. 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. Then, the corresponding impedance of the transformer is calculated for the load flow calculation. The number 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.

VVC algorithm using PSO

The proposed VVC algorithm using PSO can be expressed as follows:

- Step 1. Initial searching points and velocities of agents are generated using the above-mentioned state variables randomly.
- Step 2. Ploss to the searching points for each agent is calculated using the load flow calculation. If the constraints are violated, the 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. New velocities are calculated using (2).
- Step 5. New searching points are calculated using (3).
- Step 6. Ploss to the new searching points and the evaluation values are 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 the maximum iteration number, then go to Step 9. Otherwise, go to Step 4.
- Step 9. P-V curves for the control candidates and various contingencies are generated using 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 the next gbest and repeat the VSA procedure mentioned above.

If the voltage and power flow constraints are violated, the absolute violated value from the maximum and minimum boundaries is largely weighted and added to the objective function (1). The maximum iteration number should be determined by pre-simulation. As mentioned below, PSO requires less than 100 iterations even for large-scale problems. There are several ways to formulate VVC considering VSA. Maximization of MW margin instead of loss minimization is one option. However, the purpose of the paper is to develop VVC algorithm for steady state operation. In this case, we can think that we still have enough voltage stability margin. Therefore, the authors decided to use only loss minimization as the objective function and check whether the control strategy has enough voltage stability margins or not after loss minimization. Moreover, evaluation for each state is extremely time-consuming considering VSA during optimization procedure, and it is difficult to realize on-line VVC. Considering the trade-off between the optimal control and the execution time, the proposed method selected the way to handle the contingencies after generation of the optimal control candidates. If maximization of MW margin is required as the objective function, approximation method such as the look-ahead method with parallel computation should be used during the search procedure for on-line VVC.

VI. NUMERICAL EXAMPLES

The proposed method has been applied to several power system models compared with RTS and the enumeration method. Our target VVC problem is formulated as a MINLP with discrete and continuous variables. OPF basically only handles continuous variables and some papers such as [26] tried to handle discrete variables in OPF formulation. Unfortunately, the authors do not have OPF program with such treatment. Therefore, we compared the proposed method with the available combinatorial optimization software in the simulation.

IEEE 14 bus system

(1) Simulation conditions

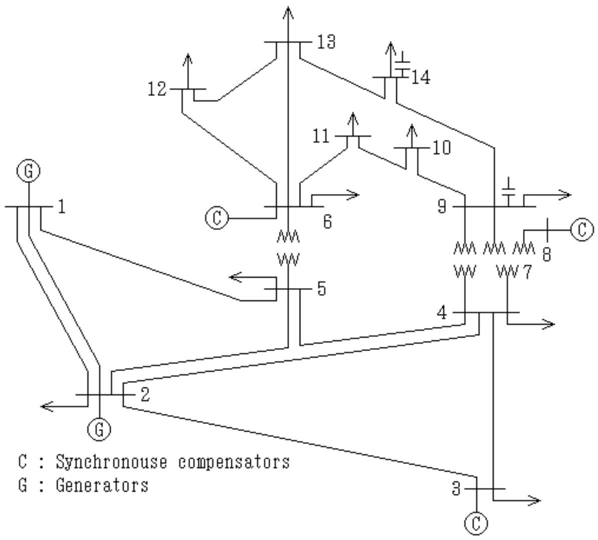


Fig. 3 A modified IEEE 14 bus system.

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

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

The proposed method tries to generate an optimal control for the operating condition. Ploss of the original system is 0.1349 [pu]. Generation of the VVC candidates (Step 1 - 7 in the proposed VVC algorithm) by the proposed PSO based method, RTS, and the enumeration method is compared in the simulation. The following parameters are utilized in the simulation according to the pre-simulation.

The coefficient function w of (2) is set to the following equation [13]:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \qquad (4)$$

where, w_{max}=0.9, w_{min}=0.4,
$iter_{max}$: maximum iteration number,
iter : current iteration number.

c_1 and c_2 of (2) are set to 2.0. w_{max} and w_{min} are set to 0.9 and 0.4 according to the pre-simulation as shown below. Number of agents for PSO is 10. The parameters for RTS are also determined to appropriate values through pre-simulation. The initial tabu length is 10 and increase/decrease rate for tabu length is 0.2 for RTS in the simulation. The results are compared with 300 searching iterations. RTS and the

Table 1 Operating condition of IEEE 14 bus system.

Bus No.	Vol. [pu]	Node specification		SC [pu]
		P [pu]	Q [pu]	
1*1	1.060	-	-	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 specification node
*3 : 0.06 [pu] * 3 SC

enumeration method utilizes digitized AVR operating values and the interval is 0.01 [pu]. The interval corresponds to 5 [kV] in 500 [kV] system. The formulation as the combinatorial optimization problem (COP) has about 10^9 combinations in the problem. The system has been developed using C language (egsc ver.1.1.1) and all simulation is performed using EWS (SPECint95: 12.3).

(2) Simulation results

Table 2 shows the best results by the proposed method, RTS, and the enumeration method. Table 3 shows the loss values and calculation time of the results. The best result by RTS is similar to that by the enumeration method (the optimal result formulated as a COP). However, the loss value calculated by PSO is smaller than the optimal value and a tap position is different between the results. When VVC is formulated as a COP, only solutions to discrete values are searched and the objective function shape between the discretized interval is out of concern. Therefore, as it is usually pointed out, the optimal solution formulated as a MINLP and a COP is different. The results indicate necessity of formulation of VVC as a MINLP. PSO can generate smaller loss values than RTS with 15 % possibility. The calculation time by PSO is about 15 % faster than that by RTS. Table 4 shows the parameter sensitivity analysis of PSO. In the simulation, w_{max} and w_{min} of (4) and c_i of (2) is changed. The average and minimum Ploss with 100 searching iterations in 100 trials for each case are shown in the table. The results reveal that the appropriate values for w_{max} and w_{min} are 0.9 and 0.4. The appropriate value for c_i is 1.5. However, the minimum Ploss for 1.5, 2.0, and 2.5 are similar and 2.0 is utilized in the simulation according to the suggested value in [13]. Consequently, the appropriate parameter values for the problem are the same as the ones suggested in [13].

The proposed method generates a P-V curve for the optimal control strategy using the CPFLOW technique and performs the voltage contingency analysis. It is verified that

Table 2 The optimal control for IEEE 14 bus system.

Method / Cont. Variables	PSO	RTS	enumeration method
AVR 2	1.0463	1.05	1.05
AVR 3	1.0165	1.02	1.02
AVR 6	1.1000	1.10	1.10
AVR 8	1.1000	1.10	1.10
Tap 4-7	0.94	0.95	0.95
Tap 4-9	0.93	0.93	0.93
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

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

Table 3 Summary of calculation results by the proposed method and reactive tabu search.

Method	compared item	IEEE 14 bus system	112 bus system
PSO	Minimum loss value	0.1332276	0.1134947
	Average loss value	0.1335090	0.1175230
	Cal. Time	16.5	54.2
RTS	Minimum loss value	0.1323657	0.1208179
	Cal. Time	19.5	220.3

loss value : active power loss [pu]
cal. time : average calculation time [s]

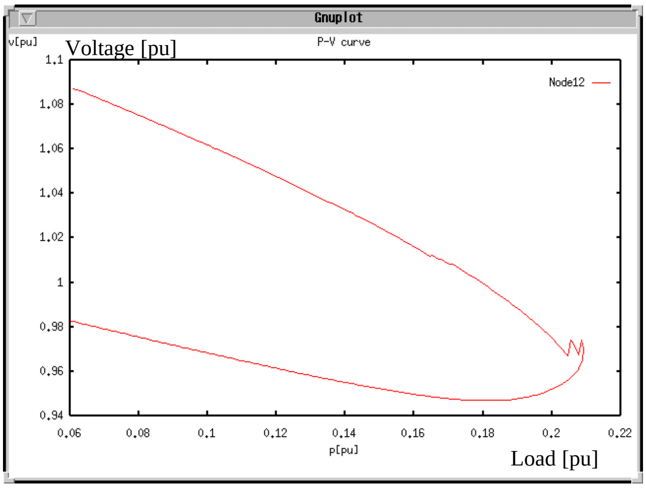


Fig. 4 A P-V curve of the optimal control (Node 12) for IEEE 14 bus system.

Table 4 Parameter sensitivity analysis for IEEE 14 bus system (100 trials).

w_{max} / w_{min}		C_i						
		0.5	1.0	1.5	2.0	2.5	3.0	4.0
0.9	ave.	0.133693	0.133573	0.133763	0.133567	0.133765	0.133986	0.134504
0.4	min.	0.133012	0.133012	0.133012	0.133012	0.133012	0.133073	0.133076
2.0	ave.	0.135519	0.135689	0.136362	0.136324	0.135763	0.136425	0.136245
0.9	min.	0.133074	0.133073	0.133073	0.133121	0.133083	0.133125	0.133315
2.0	ave.	0.134987	0.135226	0.13604	0.135661	0.135457	0.135795	0.136435
0.4	min.	0.133015	0.133012	0.133012	0.133073	0.133014	0.133075	0.133115

the strategy can keep voltage security when the load margin to 0.95 [pu] voltage is larger than 10 % load increase point in the simulation. The evaluation criteria depend on the target power system and they should be determined for each system through pre-simulation. Fig. 4 shows an example of a P-V curve for node 12 with the optimal control strategy.

Practical 112 bus model system

(1) Simulation conditions

The proposed method is applied to a practical model system with 112 buses. The system models the EHV system of Kansai Electric Practical system. The model system has 11 generators for AVR control, 47 OLTCs with 9 to 27 tap positions, and 13 SC installed buses with 33 SCs for VVC. The number of agents for PSO is set to 30 in order to get a high quality solution within 1 [min]. PSO and RTS are compared in 100 searching iterations. The same parameters for IEEE 14 bus system except the above values are utilized in the simulation.

(2) Simulation results

Fig. 5 shows the statistical evaluation results by the proposed method in 100 trials. Table 3 shows the loss values and calculation time of the results. The average loss value by the proposed method is smaller than the best result by RTS. PSO generates better solution than RTS with 96 % possibility. Fig. 6 shows typical convergence characteristics (Ploss transition of gbest by PSO and the best result by RTS). It is clear from the figure that the solution by PSO is converged to high quality solutions at the early iterations (about 20 iterations). The average iteration to the best result by the proposed method is 31.7. On the contrary, RTS reaches the best result gradually. The average calculation time by PSO is about 4 times faster than that by RTS. RTS generates neighboring solutions (candidates for the next searching point) in the solution space. It performs load flow calculation for each candidate and evaluates violation of operating constraints and tabu status for all candidates. Therefore, candidates that should be evaluated are increased exponentially as the dimension of the problem increases. On the contrary, PSO just evaluate (2) and (3) for each agent and the number of load flow calculation is the same for IEEE14 and practical 112 bus system if the same number of agents are utilized for the simulation. The characteristic of PSO is suitable for the application to practical system. The determined VVC strategy candidate is evaluated as a secure one using a CPFLOW technique. Voltage contingency analysis is also performed for the candidate and it is evaluated as secure. The calculation time for voltage contingency ranking is 11.0 [s] (112 contingencies) and the time for one CPFLOW calculation is 2.0 [s] for the 112 bus model system. Therefore, for example, the total calculation time for voltage security assessment is 19.0 [s] if CPFLOW is performed for the severest three contingencies (one CPFLOW calculation, contingency ranking and three CPFLOW calculation). As described above, large penalty is added at

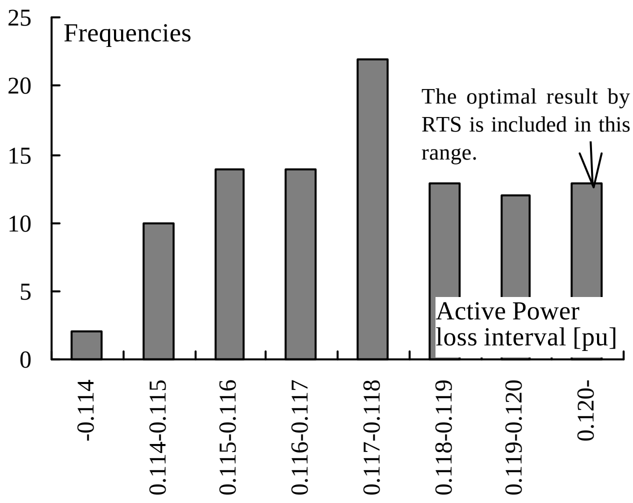


Fig. 5 Statistical results by PSO (100 trials) for practical 112 bus system.

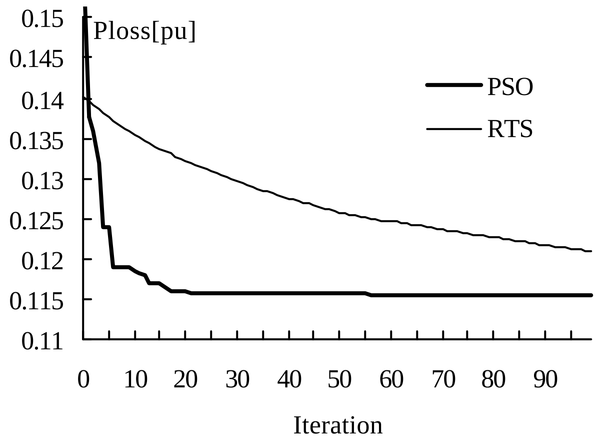


Fig. 6 Convergence characteristics by PSO and RTS for practical 112 bus system.

the evaluation of the objective function if the voltage and power flow constraints are violated. Therefore, all of the best solutions by both PSO and RTS within 100 searching iterations are feasible solutions without voltage and power flow constraints violation in the simulation. Although the best VVC strategy is evaluated as secure in the model system, voltage security assessment can become more important when the utilization rate of power equipment is increased and in the deregulation environment.

Large-scale 1217 bus model system

(1) Simulation conditions

The proposed method has been developed to apply the practical EHV system. Therefore, the applicability of the proposed method to the target system is already evaluated with the 112 bus system. However, in order to evaluate the applicability of the proposed method to large-scale systems, it has been applied to a 1217 bus system. The model system is composed by doubling the full scale Kansai Electric power system. The system has 84 generators for AVR control, 388

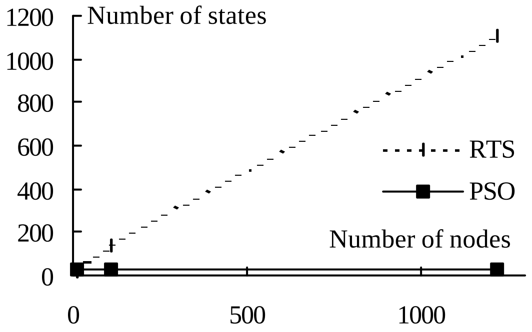


Fig.7 The number of states evaluated at each iteration by RTS and PSO.

OLTCs, and 82 SCs for VVC. The parameters for evaluated methods are the same as that utilized for the 112 bus model system.

(2) Simulation results

Convergence characteristics for the 1217 bus system by RTS and PSO are the same as Fig. 6. RTS requires about 7.6 [hour] for 100 iterations. On the contrary, the average execution time for obtaining the optimal results (the average number of iterations for that is 27.5) by PSO is about 230 [s]. Fig. 7 shows the number of states to be evaluated at each iteration by RTS and PSO. The figure assumes that the number of agent is 30 in all cases. The number by RTS is the number of neighboring states of the current state at each iteration. Therefore, it increases drastically by increase of the dimension of the problem. On the contrary, the number by PSO corresponds to the number of agents. Therefore, it is the same even for large dimensional problems. Consequently, although PSO only evaluates the limited number of states using (2) and (3), the evaluation is efficient even for the large-scale problems and realizes the quick convergence characteristic to sub-optimal solutions. The characteristic indicates the applicability of PSO to large-scale problems.

The calculation time for evaluation of one state is increasing as the dimension of the problem increases. Therefore, if speed-up of the whole execution time have to be realized, parallel computation methods based on distributed memory tools such as PVM [22] and MPI [23] or shared memory tools such as OpenMP [24] can be utilized for the optimization part in a similar manner for the VSA part.

VII. CONCLUSIONS

This paper presents a particle swarm optimization (PSO) for reactive power and voltage control (VVC) considering voltage security assessment (VSA). The proposed method formulates VVC as a mixed integer nonlinear optimization problem (MINLP) and determines a control strategy with continuous and discrete control variables such as AVR operating values, OLTC tap positions, and the number of reactive power compensation equipment. The method also considers voltage security using a continuation power flow (CPFLOW) and a voltage contingency analysis technique. The feasibility of the proposed method for VVC is demonstrated on practical power systems with promising results. The results can be summarized as follows:

(a) This paper shows the practical applicability of PSO to a MINLP and suitability of PSO for application to large-scale VVC problems. PSO has several parameters. According to the simulation results, it is not required severe parameter tuning and especially, PSO only requires less than 50 iterations for obtaining sub-optimal solutions even for large-scale systems. Many power system problems can be formulated as a MINLP and the results indicate the possibility of PSO as a practical tool for various MINLPs of power system operation and planning.

(c) VVC is sometimes formulated as a combinatorial optimization problem. However, discrete variables of the optimal result formulated as a MINLP and those formulated as a combinatorial optimization problem are different. Therefore, it indicates the efficiency of formulation of VVC as a MINLP.

(d) Consideration of VSA is one of the important practical functions of VVC. The results reveal that the possibility of treatment of the security by the proposed PSO-based method in VVC.

In addition to the proposed method, the following additional features make the proposed VVC more practical.

(d) Avoidance of control concentration to a specific equipment

(e) Tracking to load change

(f) Look-ahead control using load forecast

Especially, for handling (e)(f), an optimal control strategy in several control intervals should be considered simultaneously. Improvement of the proposed method considering the above features and parallel computation are one of the future works.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Prof. Hsaio-Dong Chiang of Cornell University for his technical supports to develop the voltage security assessment function.

REFERENCES

[1] T. Van Cutsem, T. and C. Vournas, *Voltage Stability of Electric Power Systems*, Kluwer Academic Publishers, 1998.

[2] T. Van Cutsem, "An Approach to Corrective Control of Voltage Instability Using Simulation and Sensitivity", *IEEE Transaction on Power Systems*, Vol. 10, No. 2, pp.616-622, May 1995.

[3] B. D. Thukaram, et al., "Optimal Reactive Power Dispatch Algorithm for Voltage Stability Improvement", *International Journal of Electrical Power & Energy Systems*, Vol. 18, No. 7, pp.461-468, July 1996.

[4] H. D. Chiang, et al., "CPFLOW: A Practical Tool for Tracing Power System Steady-State Stationary Behavior Due to Load and Generation Variations", *IEEE Transaction on Power Systems*, Vol. 10, No. 2, pp.623-634, May 1995.
[5] H. Yoshida, Y. Fukuyama, et al., "A Practical Continuation Power Flow for Large-Scale Power System Analysis", *Proceedings of IEE of Japan Annual Convention Record*, No. 1313, 1998 (in Japanese).
[6] K. Tomsovic, "A Fuzzy Linear Programming Approach to the Reactive Power / Voltage Control Problem", *IEEE Transaction on Power Systems*, Vol. 7, No. 1, pp.287-293, February 1992.
[7] B. Cova, et al., "Contingency Constrained Optimal Reactive Power Flow Procedures for Voltage Control in Planning and Operation", *IEEE Transaction on Power Systems*, Vol. 10, No. 2, pp.602-608, May 1995.
[8] J. L. M. Ramos, et al., "A Hybrid Tool to Assist the Operator in Reactive Power / Voltage Control and Operation", *IEEE Transaction on Power Systems*, Vol. 10, No. 2, pp.760-768, May 1995.
[9] Q. H. Wu, et al., "Power System Optimal Reactive Power Dispatch Using Evolutionary Programming", *IEEE Transaction on Power Systems*, Vol. 10, No. 3, pp.1243-1249, August 1995.
[10] H. Vu, et al., "An Improved Voltage Control on Large-Scale Power System", *IEEE Transaction on Power Systems*, Vol. 11, No. 3, pp.1295-1303, August 1996.
[11] T. L. Le et al., "Network Equivalents and Expert System Application for Voltage and VAR Control in Large - Scale Power Systems", *IEEE Transaction on Power Systems*, Vol. 12, No. 4, pp.1440-1445, November 1997.
[12] J. Kennedy and R. Eberhart, "Particle Swarm Optimization", *Proceedings of IEEE International Conference on Neural Networks*, Vol. IV, pp.1942-1948, Perth, Australia, 1995.
[13] Y. Shi and R. Eberhart, "A Modified Particle Swarm Optimizer", *Proceedings of IEEE International Conference on Evolutionary Computation*, pp.69-73, Anchorage, May 1998.
[14] H. Zhenya, et al., "Extracting Rules from Fuzzy Neural Network by Particle Swarm Optimization", *Proceedings of IEEE International Conference on Evolutionary Computation*, pp.74-77, Anchorage, May 1998.
[15] J. Kennedy and W. Spears, "Matching Algorithm to Problems: An Experimental Test of the Particle Swarm Optimization and Some Genetic Algorithms on the Multimodal Problem Generator", *Proceedings of IEEE International Conference on Evolutionary Computation*, pp.78-83, Anchorage, May 1998.
[16] P. Angeline, "Using Selection to Improve Particle Swarm Optimization", *Proceedings of IEEE International Conference on Evolutionary Computation*, Anchorage, pp.84-89, May 1998.
[17] A. M. Geoffrion, "Generalized Benders Decomposition", *Journal of Operation Theory and Applications*, Vol.10, No.4, pp.237-260, 1972.
[18] G. R. Kocis and I. E. Grossmann, "Computational Experience with DICOP solving MINLP Problems in Process Systems Engineering", *Computer Chemical Engineering*, Vol.13, No.3, pp.307-315, 1989.
[19] R. Battiti, "The Reactive Tabu Search", *ORSA Journal of Computing*, Vol.6, No.2, pp.126-140, 1994.
[20] Y. Fukuyama, et al., "A Reactive Tabu Search for Service Restoration in Electric Power Distribution Systems", *Proceedings of IEEE International Conference on Evolutionary Computation*, Anchorage, pp.763-768, May 1998.
[21] H. D. Chiang, H. Yoshida, Y. Fukuyama, et al., "The Generation of ZIP-V Curves for Tracing Power System Steady State Stationary Behavior to Load and Generation Variations", *Proc. of IEEE Summer Meeting*, July 1999.
[22] H. D. Chiang, et al., "Look-ahead Voltage and Load Margin Contingency Selection Functions for Large-scale Power Systems", *IEEE Transaction on Power Systems*, Vol.12, No.1, pp.173-180, February 1997.
[23] J. Dongarra, et al., *PMV 3 User's Guide and Reference Manual*, Oak Ridge National Laboratory, May 1993.
[24] W. Gropp, et al., *Using MPI*, The MIT Press, 1994.
[25] *OpenMP C and C++ Application Program Interface Version 1.0*, OpenMP Architecture Review Board, October 1998.
[26] W. E. Liu, A. D. Papalexopoulos, and W. F. Tinney, "Discrete Shunt Controls in a Newton Optimal Power Flow", IEEE Trans. on Power Systems, Vol.7, No.4, November 1992.

HIROTAKA YOSHIDA received M.S. degree in electrical engineering in 1976 from Doshisha University, Kyoto, Japan. He has been working at The Kansai Electric Power Co. from 1976. His research interests include analysis, planning, and operation of power systems. He is a member of IEE of Japan.

KENICHI KAWATA received M.S. degrees in electronics engineering in 1977 from Osaka University, Osaka, Japan. He has been working at The Kansai Electric Power Co. from 1977. His research interests include development of operation and control method in power systems.

YOSHIKAZU FUKUYAMA (M'90) received the B.S., M.S., and Ph.D. degrees in electrical engineering in 1985, 1987, and 1997, respectively, from Waseda University, Tokyo, Japan. He has been working at Fuji Electric Co. R&D Japan from 1987. He was a visiting scientist at Cornell University from 1993 to 1994. His research interests include application of intelligent systems to power systems and power system analysis. He is a member of IEEE and IEE of Japan.

SHINICHI TAKAYAMA received the B.S. and M.S. degrees in electrical engineering in 1996 and 1998, respectively, from Hosei University, Tokyo, Japan. He has been working at Fuji

Electric Co. R&D Japan from 1998. His research interests include application of modern heuristic techniques to power systems. He is a member of IEE of Japan.

YOSUKE NAKANISHI (M'88) was born in Hyogo, Japan on January 6, 1955. He received B.S. and M.S. in Electrical Engineering from Waseda University and Ph.D. from Tokyo Metropolitan University in 1978, 1980, 1996, respectively. He joined Fuji Electric Co. in 1980 and is currently working as a senior engineer at Fuji Electric Co. R&D. His research interests include simulation and analysis of voltage problems of electric power systems. He is a member of the IEE of Japan and IEEE.