The 1999 IEEE Systems, Man, and Cybernetics Conference (SMC'99)
Tokyo International Forum, Tokyo, Japan Oct.12 - 15, 1999

A Particle Swarm Optimization for Reactive Power and Voltage Control in Electric Power Systems Considering Voltage Security Assessment

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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 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.

1. INTRODUCTION

One of the important operating tasks of power utilities is to keep voltages within an allowable range for high quality customer service. Electric power loads varies from hour to hour and voltages can be varied by the power load change. Power utility operators in control centers control various equipment such as generators, transformers, static condenser (SC), and shunt reactor (ShR), so that they can inject reactive powers and control voltages directly in target power systems to follow the load change. VVC determines an on-line control strategy for keeping voltages 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. Reduction of power generation cost is one of the current interested issues of power utilities. Therefore, 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 problem has 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 P-V curve using continuation power flow (CPFLOW)[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 sufficient distance can be kept for both calculations, the new operating condition calculated by VVC can be evaluated as a secure condition. 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 (SC, ShR, etc). 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 a 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. Since PSO can handle such constraints easily, it is suitable for VVC.

This paper presents a PSO for a VVC problem formulated as a MINLP considering VSA. 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.

2. PROBLEM FORMULATION OF VVC

Problem Formulation

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

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

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 their permissible ranges to maintain power quality.

(b) Power flow constraint

Power flow of each branch must lie within their permissible ranges.

(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. P-V curve for the determined VVC strategy and various contingencies can be generated and checked whether the VVC candidate can keep sufficient voltage security margins.

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*)

AVR operating values are treated as voltage specified values in load flow calculation. 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.

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

PSO has been developed through simulation of simplified social models. 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 feature is suitable for VVC problem because practically efficient methods have not been developed for VVC with both continuous and discrete variables.

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. 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 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.

Searching procedures by PSO based on the above concept can be described as follows: a flock of agents optimize 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:

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

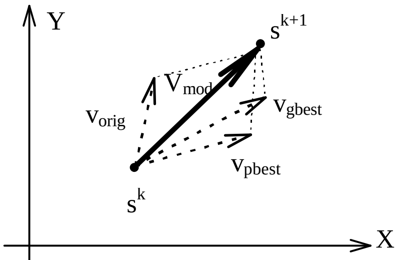
where, v_i^k : velocity of agent i at iteration k,
rand : random number between 0 and 1,
s_i^k : current position of agent i at iteration k,
$pbest_i$: pbest of agent i,
gbest : gbest of the group,
w_i : weight function for velocity of agent i,
c_i : weight coefficients for each term.

Using the above equation, a certain velocity that gradually gets close to pbests and gbest can be calculated. The current position can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{3}$$

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



S^k : current searching point,
s^{k+1} : modified searching point,
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.

(b) The first term of right-hand side of (2) is corresponding to global search. The second and third terms of that are corresponding to local search. Namely, the method has a well-balanced mechanism to utilize global and local search efficiently.
(c) The original method can be applied to the continuous problem. However, the method can be expanded to the discrete problem using 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 original PSO has been applied to a learning problem of neural networks and Schaffer f6, the famous benchmark function for GA, and efficiency of the method has been confirmed [12].

4. VOLTAGE SECURITY ASSESSMENT

P-V curve represents the relation between load increase and voltage drop. Namely, 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 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 (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 [21]. 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 security by the control or not.

5. 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 (agents) and velocities 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, 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 and searching points are calculated using (2) and (3).
Step 5. Ploss to the new searching points and the evaluation values are calculated.
Step 6. 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 7. If the iteration number reaches the maximum iteration number, then go to Step 9. Otherwise, go to Step 4.
Step 8. 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 next gbest and repeat the procedure.

6. NUMERICAL EXAMPLES

IEEE 14 bus system

(1) Simulation conditions

Fig. 2 shows a modified IEEE 14 bus 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 generates an optimal control for the operating condition. Ploss of the original system is 0.1349 [pu].

Generation of the VVC candidates (Step 1 - 6 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 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 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).

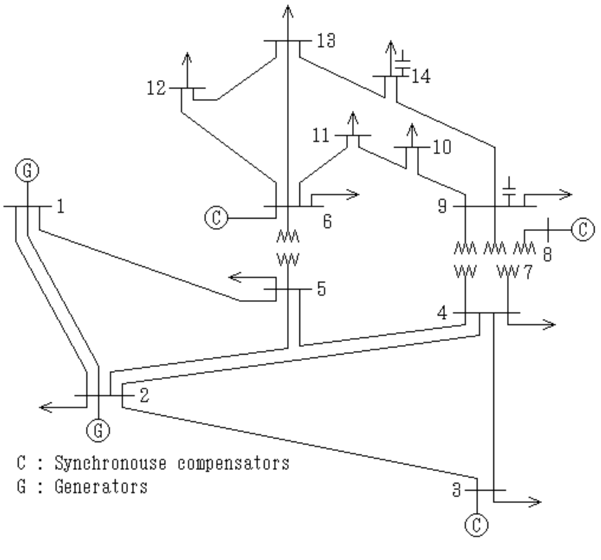


Fig. 2 A modified IEEE 14 bus system.

(2) Simulation results

Table 1 shows the best results by the proposed method, RTS, and enumeration method. Table 2 shows the loss values and calculation time of the results. The best result by RTS is similar to that of 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.

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 the

Table 1 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 2 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]

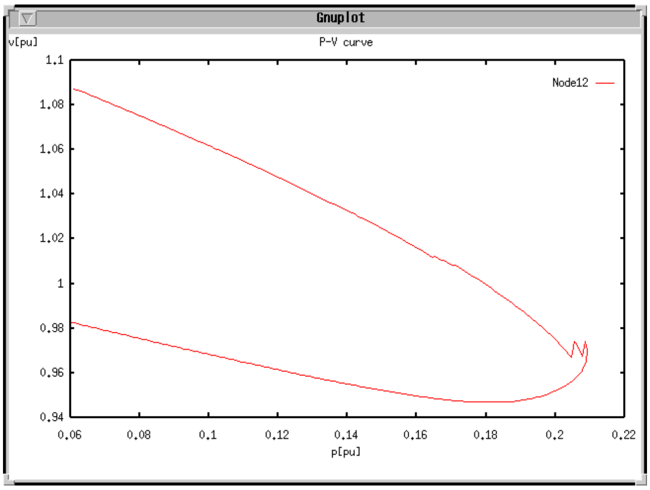


Fig. 3 A P-V curve of the optimal control (Node 12) for IEEE 14 bus system.

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 it should be determined for each system through pre-simulation. Fig. 3 shows an example of P-V curve for node 12 with the optimal control strategy.

Practical 112 buses 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. 4 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. 5 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 a high quality solution 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 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).

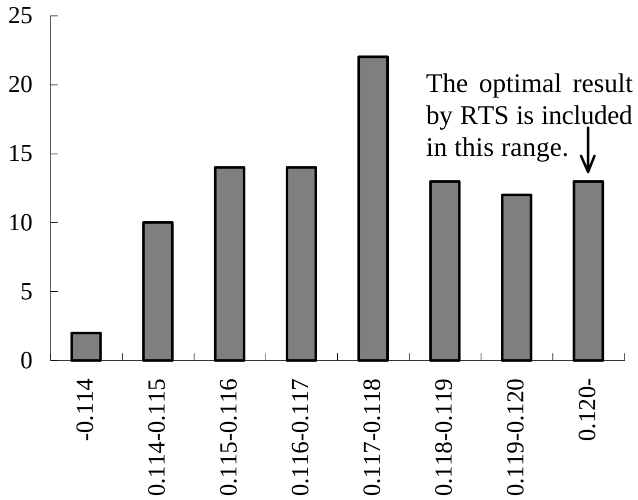


Fig. 4 Statistical results by PSO (100 trials).

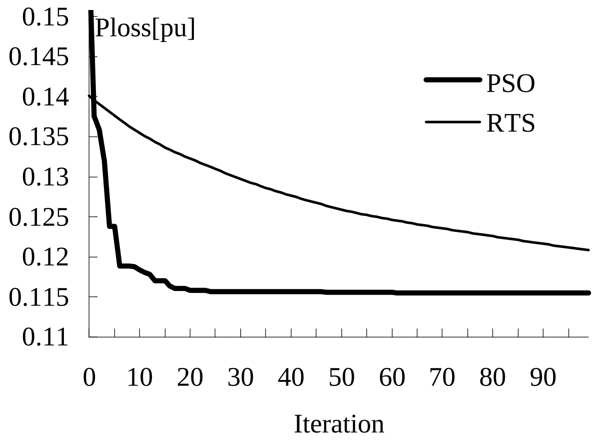


Fig. 5 Convergence characteristics by PSO and RTS for practical 112 bus system.

7. 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 problem as a mixed-integer nonlinear optimization problem (MINLP) and determines 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 voltage contingency analysis techniques. 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 VVC problem. Many power system problems can be formulated as a MINLP and the results of the paper indicate the possibility of PSO as a practical tool for power system operation and planning.
(b) 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 and it indicates the efficiency of formulation of VVC as a MINLP.
(c) 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.

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. The proposed method will be improved considering the above features for 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.

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