Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

A Tabu Search Based Method for Optimal Allocation of D-FACTS in Distribution Systems

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Abstract: This paper proposes a tabu search based method for optimal allocation of FACTS in distribution systems. Distributed generation is wildly spread to smooth operation and planning in power systems so that wind power generation units are connected to distribution systems. Although they contribute to the improvement of operation and planning in distribution systems, they often bring about difficulties that the existence of reverse power flows causes the voltage and frequency fluctuations due to uncertain generation output. In this paper, a new meta-heuristic optimization method is proposed to control the voltage deviations caused by wind power generation. It is necessary to determine the optimal allocation and the output variable of power controllers (D-FACTS) for uncertain wind power generation. This paper presents the Monte Carlo simulation method that determines the optimal allocation and the output variable of the controllers and evaluates the voltage security assessment in a probabilistic way. This paper is successfully applied to the IEEE 32-node distribution system.

1. INTRODUCTION

In recent years, the liberalization of power systems has been widely spread in the world. New players take part in power markers to make profit through selling and purchasing electricity so that power systems become more deregulated and competitive. As a result, distribution generation units are introduced into distribution systems to smooth distribution system operation and planning. The use of distribution generation supplement power supplies from the distribution substation. As the typical distributed generation, the followings are well-known:

1) wind power generation

2) solar photovoltaic power generation

3) micro gas turbine

4) fuel battery

This paper focuses on item 1) above. Wind power generation is attractive in a sense that wind power generation is clean and inexhaustive energy. As sustainable energy, wind power generation has been widely-spread to deal with global warming. However, there is a challenge that the reverse flows occur in distribution systems with wind power generation units. Although the power flows traditionally runs from the distribution substation to the ending nodes in distribution systems, the distribution system with wind power generation creates the reverse flows that stream from the ending nodes to the substation because they are often installed at the ending nodes as supplementary power sources. In addition, the wind power generation output that is affected by weather conditions varies randomly and brings about fluctuations to distribution systems. As s result, they cause the uncertain variations on nodal voltages and frequency. To maintain the power quality, it is necessary to control the voltage and frequency in distribution systems.

In this paper, a Monte-Carlo-simulation based method is proposed to keep the voltage profile with D-FACTS devices that are power controller devices for distribution systems to improve the power quality (Reed, *et al.*, 2000). D-FACTS mean FACTS (Flexible AC Transmission Systems) (Hingorani, 1993) that are diverted to distribution systems. A lot of studies on the optimal allocation of FACTS for transmission systems have been done. FACTS devises were used for improving loadabilty (Mori and Goto, 2000; Gerbex *et al.*, 2001; Gerbex, *et al.*, 2002; Mori and Maeda, 2006a, 2006b), OPF (Galiana *et al.*, 1996; Leung and Chung, 2000), security assessment (Song *et al.*, 2004), *etc.* On the other hand, the studies on the optimal allocation of FACTS for distribution systems have not been done although FACTS devices were locally introduced into distribution systems (Reed, *et al*., 2000). In this paper, a method for the optimal allocation of D-FACTS is developed to suppress the voltage deviations. The problem formulation of the optimal allocation of D-FACTS is to determine the location and the output variable of D-FACTS so that the deviation of the nodal voltage is minimized. Since this problem is hard to solve due to the nonlinearity and the complexity of combinatorial optimization, it is important to evaluate better solutions from a standpoint of global optimization. A tabu search (TS) based method is used to evaluate the location and the output variable of D-FACTS for a snapshot of wind power generation. TS is one of meta-heuristics that repeatedly makes use of simple rules or heuristics to evaluate better solutions. Meta-heuristics is very useful for solving a combinatorial optimization problem in a sense that it gives a global optimal solution or its highly approximate solutions within a time frame. As meta-heuristics, TS provides better solutions in comparison with SA (Simulated Annealing) (Kirkpatrick, *et al.*, 1983) and GA (Genetic Algorithms) (Goldberg, 1989). However, it is not easy to evaluate two kinds of variables, *i.e.*, the location and the output variable of D-FACTS. This paper presents a two-layered TS method for determining the location and the output variable of D-FACTS. Layer 1 evaluates the optimal location while Layer 2 calculates the optimal output variable. After carrying out Layer 1, Layer 2 optimizes the variable. The process of Layers 1 and 2 is repeated until the termination conditions are satisfied. Also, to consider a set of scenarios of wind power generation output, the Monte-Carlro simulation is used to evaluate the voltage security assessment in a probabilistic way. The effectiveness of the proposed method is demonstrated in the IEEE 32-node distribution systems.

2. OPTIMAL ALLOCATION OF D-FACTS

In this section, the formulation of the optimal allocation of D-FACTS is described. In 1983, Hingorani proposed FACTS that were power-electronics-based apparatus to deal with fast power flow control efficiently (Hingorani, 1983). FACTS make use of branch admittance, nodal voltage magnitudes, and/or nodal voltage angles to change line flows so that the transmission capacity, loadability, network losses, and/or security assessment are improved. As typical FACTS devices, the followings are often used:

a) SVC and STATCOM

b) TCSC and TCPAR

c) UPFC

SVC and STATCOM are the apparatus for controlling reactive power. TCSC and TCPAR work to adjust active power control. UPFC has the function of controlling active and reactive power. The optimal placement of FACTS for transmission systems has been positively studied. In recent years, the introduction of FACTS into distribution systems is required to handle the complicated conditions that the liberalization of power systems is spread and the distribution generation units are installed to distribution systems. Wind power generation gets a lot of attention due to clean and inexhaustive energy. On the contrary, the occurrence of the reverse flow brings about the uncertainty of power flows and large voltage deviations. As a result, it is necessary to install FACTS devices in distribution systems. This paper considers the optimal allocation of SVC that is easily installed in distribution systems from a standpoint of cost. The mathematical formulation of the optimal allocation may be written as

Cost function:

$$f(x) \to \min \qquad (1)$$

Constraints:

$$g_1(\boldsymbol{x}) = 0 \qquad (2)$$

$$g_2(\boldsymbol{x}) \le 0 \qquad (3)$$

where

f: cost function

g_1: equality constraints

g_2: inequality constraints

$\boldsymbol{x}$: state vector

Eqn. (1) means the cost function that minimizes the nodal voltage magnitude deviations. Eqn. (2) shows the power flow equation. Eqn. (3) gives the lower and the upper bounds of nodal voltage magnitudes and so on. Eqn. (1) is minimized by optimizing the location and the output of SVC while satisfying Eqns. (2) and (3). To solve the problem above, a TS-based method is proposed.

3. TABU SEARCH

This section describes Tabu Search (TS) that is one of meta-heuristics that are useful for solving a combinatorial optimization problem efficiently (Glober, 1989;. Glober, 1990). Meta-heuristics is defined as an algorithm that iteratively makes use of simple rules or heuristics to obtain a better solution. The main difference between the meta-heuristics and conventional methods is that the meta-heuristics have a function to escape from a local minimum. As the meta-heuristics, SA, GA and TS are well known in power systems. TS has the following features:

-It makes use of the adaptive memory called tabu list to escape from a local minimum and find out a better solution.
-The basic idea of TS is based on the hill-climbing method of local search.
-It has only one parameter referred to as tabu length that shows the length of the tabu list.

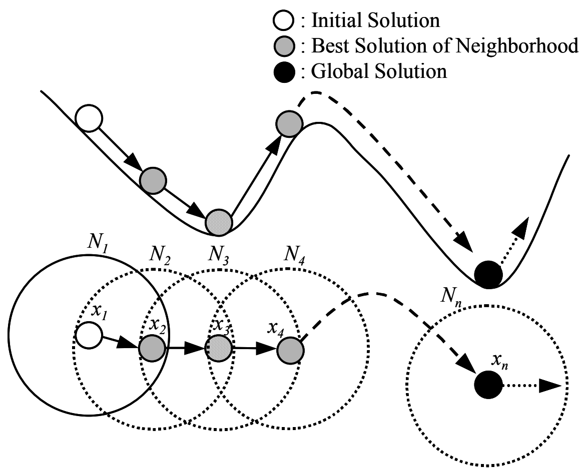

Fig. 1 Concept of Tabu Search

TS is based on the hill-climbing method. The hill-climbing method moves to the solution at each iteration after making solution candidates in the neighborhood around a solution, selecting the best one and regarding it as an initial solution at the next step. It easily gets stuck in a local minimum due to local search. On the other hand, However, TS allows the solution to escape from a local minimum with the tabu list. It introduces the tabu list of the adaptive memory into the hill-climbing method to prevent the solution from staying at a local minimum. The tabu list serves as a function that some attributes are fixed for a period. That allows iterative solutions to escape from a local minimum. Fig. 1 shows the search process of TS, where x_i denotes an initial solution in the neighborhood and N_i indicates the neighborhood at iteration i. The algorithm of TS may be summarized as follows:

Step 1: Set the initial conditions (initial solution x_0, iteration count i =0).
Step 2: Create the neighborhood around x_i.
Step 3: Select the best solution in the neighborhood with the function of the tabu list.
Step 4: Stop if the terminal conditions are satisfied. Otherwise, set $i = i + 1$ and return to Step 2.

4. PROPOSED METHOD

This section proposes a TS-based method for determining the location and the output variable of SVC devices to suppress the nodal voltage deviations in distribution systems with uncertain wind power generation units. The proposed method makes use of two-layered TS in which Layer 1 evaluates the optimal location of SVC and Layer 2 determines the output variable of SVC. Fig. 2 depicts the concept of two-layered TS, where based on the neighborhood solutions at Layer 1, the optimal output variable is evaluated at Layer 2 that carries out neighborhood search as shown in Fig. 3. After calculating the best output variable at Layer 2, Layer 1 cerates the neighborhood solution around the previous solution and selects the best solution. The search process between Layers 1 and 2 is repeated until the termination conditions are satisfied. The location of SVC is determined by solving a combinatorial optimization problem with TS at Layer 1 since the location is expressed in discrete number. In the same way, the output variable is evaluated by TS after the SVC output variable in continuous number is represented in discrete number. Therefore, the proposed method deals with the combinatorial optimization problems at Layers 1 and 2. Also, this paper reformulates DistFlow (Baran and Fu, 1989a, 1989b) in a way that the ending nodes have P-Q constant loads of wind power generation. Taking a lot of scenarios of wind power generation patterns into account, this paper presents the Monte-Carlo simulation for evaluating the nodal voltage profile for uncertain wind power generation output in a stochastic way.

Next, the specific problem formulation is outlined. This paper aims at minimizing the largest voltage deviation. Let us consider the following mathematical formulation:

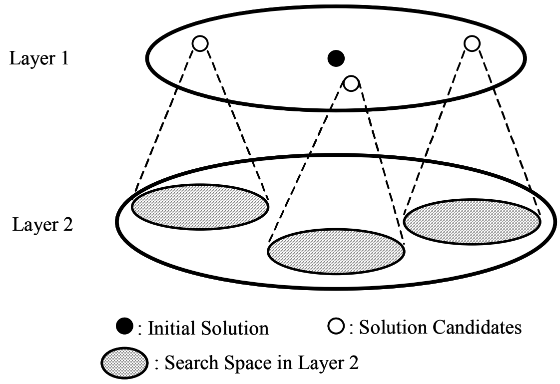

Fig. 2 Concept of Two-Layer Structure.

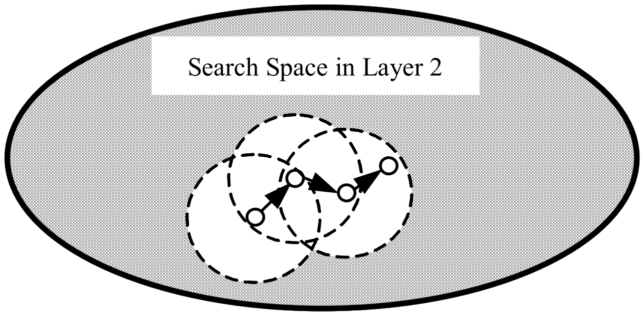

Fig. 3 Search Process in Layer of TS.

Cost functions:

Layer 1:

$$f_j = \sum_{k=1}^{m} g_{j,k} \rightarrow \min \tag{4}$$

Layer 2:

$$g_{j,k} = \max_i |V_i - V_{is}| + p \rightarrow \min \tag{5}$$

$(i=1,2,\ldots, n)$

Constraints:

The power flow equation (DistFLow) with the ending node of PQ load

$$V_i^m \le V_i \le V_i^M \tag{6}$$

$$0 \le Q_i^{SVC} \le Q_M^{SVC} \tag{7}$$

where

f_j: cost function for SVC allocation pattern j

$g_{j,k}$: cost function for SVC output variable for SVC allocation pattern j with wind power generation output k

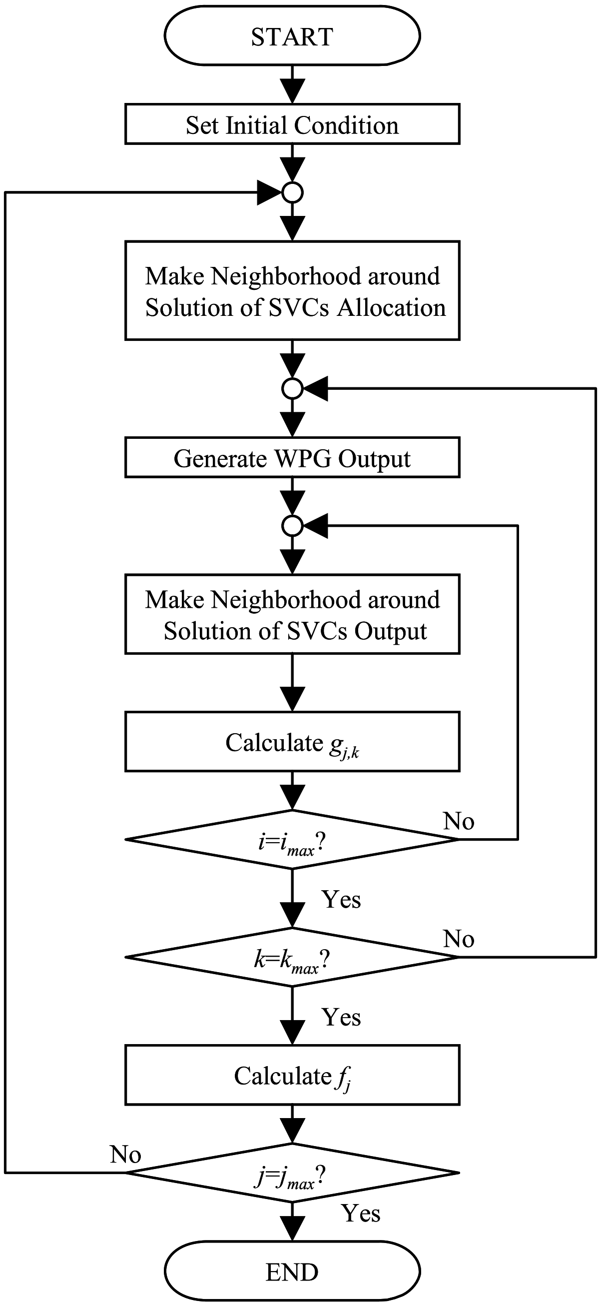

Fig. 4 Flowchart of Proposed Method

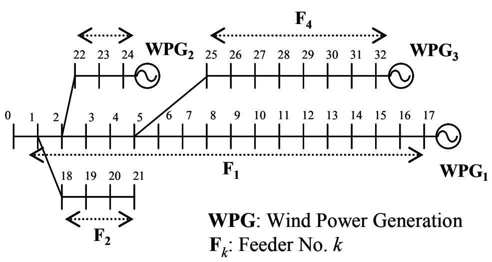

Fig. 5 Sample System

m: number of random wind power generation patterns

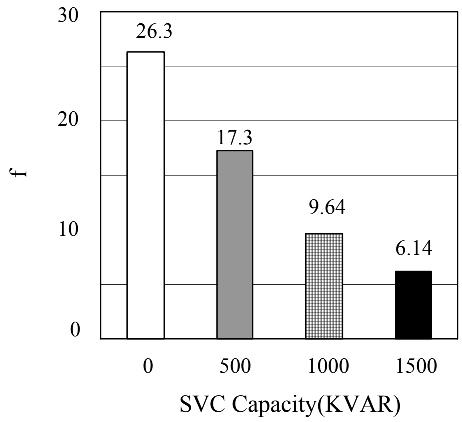

Fig. 6. Comparison of Cost Functions.

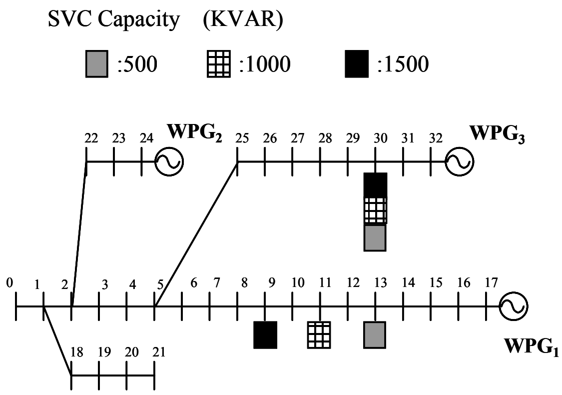

Fig. 7 Optimal Allocation of SVC

V_{is}: reference voltage magnitude at node i

n: number of nodes in a distribution system

p: penalty to violate the constraints

$V_i^m(V_i^M)$: lower(upper) bound of nodal voltage V_i

It should be noted that this paper has two cost functions since the problem to be solved is decomposed into Layers 1 and 2. Eqn. (4) shows the cost function for determining the optimal allocation of SVC that is based on the sum of $g_{j,k}$. Eqn. (5) implies the cost function for evaluating the optimal output variable of SVC for wind power generation pattern k. It minimizes the largest voltage deviation. For m wind power generation patterns, m kinds of cost functions exist. Based on Eqn. (5), Eqn. (4) is calculated to optimize the location of SVC. Term p in Eqn. (5) means the penalty to violate the constraints above.

To solve the problem, this paper makes use of two-layered TS that determines the optimal allocation of SVC at Layer 1 and optimizes the output variable of SVC at Layer 2. Fig. 4 shows the flowchart of the algorithm, where the search process loop of SVC variable is set inside that of the SVC optimal allocation is set outside. Taking uncertain wind power generation into account, this paper carries out the

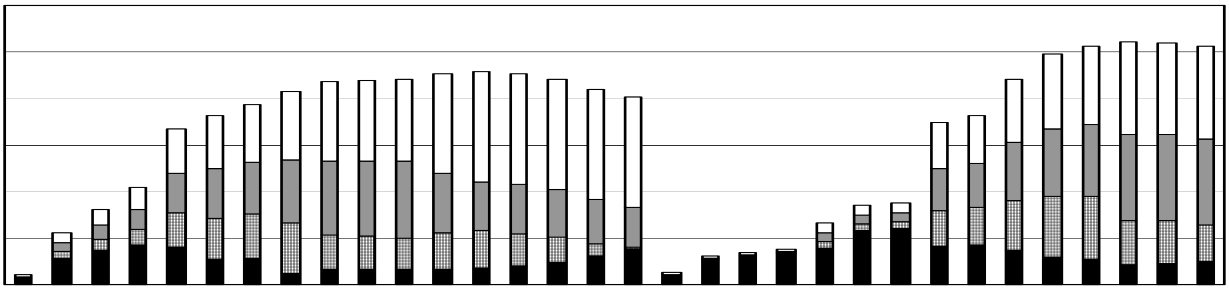

Fig. 8 Average Voltage Deviation at Each Node

Monte Carlo simulation in a way that wind power generation output is randomly created. As a result, the algorithm consists of triple loops.

5. SIMULATION

5.1 Simulation Conditions

The proposed method is applied to the 32-node distribution system (Baran and Wu, 1989c), where the original system is changed in a way that ending nodes 17, 24 and 32 have wind power generation units. For convenience, the following feeders are defined:

Feeder F_1: feeder from node 1 to node 17
Feeder F_2: feeder from node 18 to node 21
Feeder F_3: feeder from node 22 to node 24
Feeder F_4: feeder from node 25 to node 32

The load conditions are the same as the original system except the ending nodes. The reference voltage (V_{is}) is set to be the voltage magnitude at the distribution substation. Each node has the following upper and lower bounds:

$$0.9 \le V_i \le 1.1 \qquad (8)$$

The Monte-Carlo simulation is used to generate the wind power output at the ending nodes randomly. The number of trials is 500. It has the following upper and lower bounds:

$$0 \le V_i \le 700(KW) \qquad (9)$$

It is assumed that the wind power generation has the fixed factor of 1.0. This paper installs two SVC devices that have three capacity of 500, 1000 and 1500(KVAR).

5.2 Simulation Results

Fig. 6 shows the comparison of cost functions before and after installing SVC of 500, 1000, and 1500(KVAR). Installing SVC improved 34.3, 63.3 and 76.6 % for 500, 1000, and 1500 cases, respectively. Fig. 6 gives the results of the optimal allocation of SVCs for each case.. It can be seen that 500, 1000, and 1500 cases select 13 and 30, 11 and 30, 9 and 30 as the optimal location, respectively. In other words, it is effective to install SVCs at Feeders F1 and F2. Also, as the capacity of SVC increase, the place to be installed gets away from the ending nodes.

6. CONCLUSIONS

This paper has proposed a TS-based method for determining the optimal allocation of D-FACTS in distribution networks with uncertain wind power generation units. The proposed method is based on a two-layered optimization technique of TS in which Layer 1 deals with the optimal location of SVCs and Layer 2 determines the optimal output variable. The proposed method was applied to the 32-node distribution systems with three wind generation units. The simulation results have shown that the proposed method succeeded in reducing the voltage deviation under uncertain wind power generation conditions.

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