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# Coordinated Allocation and Control of Voltage Regulators at the Minimum Cost Based on Reactive Tabu Search

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*Abstract:* - This paper proposes a coordinated allocation and control of Step voltage regulators (SVRs) and Static Var Compensators (SVCs) for voltage deviations in case distributed generators are installed in distribution networks. In the proposed method, the reactive tabu search (RTS) with multiple structures and functions has been applied to the coordination. Firstly, the locations of SVRs are selected optimally and secondly the tap positions of SVRs are optimized by the RTS. Finally, the locations of SVC are decided to brush up the voltage profile in the distribution network. The proposed method enables us to take account of the installation cost of both SVR and SVC as an economic criterion, the upper and lower limit of voltage at each node and also the upper limit of line currents as constraints. By applying the proposed method to a practical distribution test system, it is verified that this method is efficient to allocate SVRs and SVCs at the minimum cost and regulate the system voltages within an appropriate value after introducing distributed generators into the distribution system.

*Key-Words:* - Expansion planning, Tabu search, SVR, SVC, Distribution system, Distributed generator

## 1 Introduction

The deregulation of electric power industries and electricity supply systems effectuated from 2005 in Japan has given birth to various new power producers who are enable to sell the retail electricity to customers contracting to grids with the high voltage and more than 50kW-capacity contracted customers. From above, it is expected that various distributed generators would be further connected to distribution systems. Some customers can utilize higher quality electric power due to purchase of electricity from distributed generators in the vicinities. On the contrary, other customers with the environment consciousness would select to buy electricity from renewable energy-use generators such as, wind energy and photovoltaic systems. However, connecting renewable energy generators to the electrical power system might cause some anxiety, since it can lead to deterioration of the quality in power supply. The renewable energy resources are influenced by the weather and then the power output is not predictable. For these reasons, it is required to introduce proper regulating devices that are able to suppress the voltage deviation at the location near the distributed generators. Furthermore, since most of the countries including Japan have a large investment rate for equipments in energy delivery systems, it is essential to allocate those equipments and control devices effectively at the selected sites and by the limited capacities to reduce the installation costs.

In distribution systems, the voltage control has been performed by utilizing the LDC (Line Drop Compensation) function of the SVR (Step Voltage Regulator), which can be installed at banks of distribution substations and also near each feeder whenever it is required. However, SVR needs more than five minutes to change the tap position for keeping voltages, then SVR cannot respond to transitional voltage fluctuation such as voltage flicker and voltage sag caused by distributed generators [1].

SVC (Static Var Compensator) is fast enough to respond to transitional voltage fluctuations and SVC can keep the voltage constant at the installation point by controlling reactive powers. However, if only SVCs are used as the voltage control, large installation capacities of SVCs are needed and this brings huge cost because SVCs are expensive.

Under such circumstances, this study proposes an optimal coordinated allocation and control approach for SVRs at the minimum cost as well as SVCs that can respond to rapid voltage fluctuations but is costly. The expansion-planning problem is formulated as a large scale combinatorial optimization problem. So it is difficult to solve within a practical time by the precise method such as Dynamic Programming (DP), Branch and Bound method (B&B) and so on [10]. From this reason, in this paper, we proposed to utilize Reactive tabu search (RTS). Tabu Search (TS) is known to be able to search the global solution within a certain practical time [7,8]. Additionally, the number of parameters of TS is small compared with other meta-heuristic methods such as Genetic algorithm (GA) and Simulated Annealing (SA) and so on. So, it is easy to apply to practical problems [5]. However, distribution systems form various structures due to topography and demand patterns in the area. Then, in optimizations, it is hard to adjust tabu length, which is only one parameter in TS, according to structures in preprocess. RTS can control tabu length automatically and avoid the loop of search [4,9]. Therefore, a modified reactive tabu search with multiple structures is proposed and is applied to a standard distribution test system to verify its practicability and performance.

# 2 Formulation

## 2.1 Formulation of the method

In this distribution expansion planning, the purpose is to minimize the cost of installing voltage control devices and to keep voltage within the prescribed value. It enables us to allocate the voltage control equipment more effectively to allocate both SVR and SVC coordinately.

This paper proposes a comprehensive approach to install SVRs and SVCs simultaneously. As the options for the installation planning, replacement and extended installation of SVRs and SVCs can be selected.

The objective function of the coordinated allocation of the equipments can be formulated as follows:

$$f = \min\left[ C(X,E) + \sum_{t}^{n} \left[ w_1 \sum_{j=1}^{m} (V_j - V_{ref})^2 + w_2 g(V,I) \right] \right] \quad (1)$$

Where, $f$ :objective function

$w_k$: weighting factor on each objective,

$V_{ref}$: reference voltage,

$g(V,I)$ : sum total deviation from voltage and current constraints,

$C$: installation and replacement cost of equipment

$X$: the number of installed SVRs or SVCs,

$E$: type of equipments

$n$: the number of time series data

$m$: the number of nodes

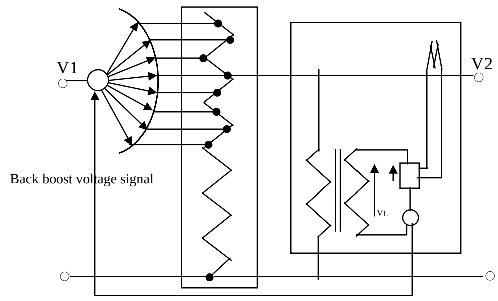


Fig.1 Structure of SVR

The following constraints should be taken into consideration in the distribution expansion planning.

The upper and lower limit of voltages:

$$V_{ref} - V_{band} \le V_i \le V_{ref} + V_{band} \quad (2)$$

Where,

$V_{band}$: permissible range of voltage.

Power flux upper limit on transmission lines:

$$\left| P_{ij} \right| \le P_{ij}^{\max} \quad (3)$$

This shows that the current or power flux at each line must be within its permissible range.

The distribution expansion planning formulated here is a combinatorial optimization problem to minimize the multi-attribute objective function as shown in the equation (1), for optimizing the number and locations of SVRs and SVCs, fulfilling the constraints on voltages and currents. It will be solved using the Back and Forward Sweep (BFS) method.

## 2.2 Structure and Function of SVR and SVC

A SVR which is shown by figure 1 has been used to control the voltage in distribution systems. The SVR changes the tap position automatically for keeping the prescription voltage to respond to voltage fluctuation caused by load change. However, SVRs can not respond to rapid transitional voltage fluctuations because SVR needs more than five minutes to change a tap position for keeping voltages.

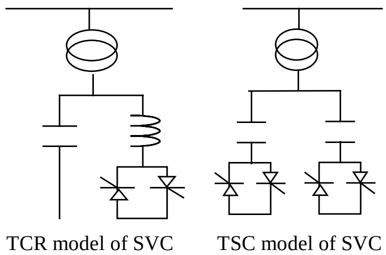


Fig.2 Structure of SVC

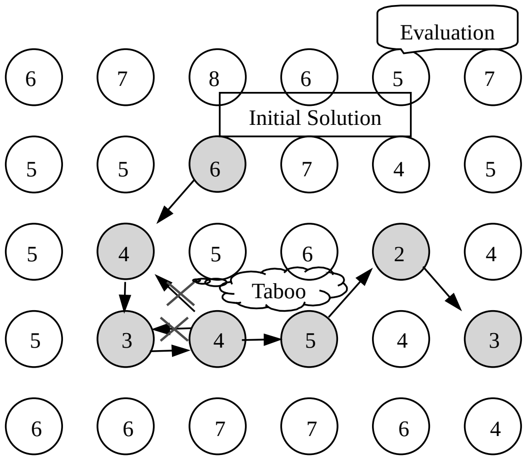


Fig.3 Concept of Tabu Search

Figure 2 shows the structure of SVC. The SVC is a device which controls reactive powers in power systems and is composed of a condenser and a reactor. SVC is able to response to a steep voltage fluctuation occurred by distributed generators. However the cost of SVCs is more expensive than that of SVRs. Therefore, it is indispensable to evaluate how much capacity should be installed to the system. From the above-mentioned, in the optimal allocation problem, we try to decrease the installed capacity of SVCs and the total equipment investment cost by allocating SVRs and SVCs coordinately.

# 3 Procedure of Reactive Tabu Search

## 3.1 Optimization Process by Tabu Search

In Tabu Search (TS), a number of state transitions in the search space are carried out aiming at finding out the optimal solutions or a range of near optimal solutions. The terminology of Tabu is related to the characteristic that in the optimization process the method avoids revisiting certain areas of the search space that have already been searched [5,7,8]. Figure 3 shows the concept of Tabu Search method.

## 3.2 Advantages of Reactive Tabu Search

It was mentioned that the Tabu search has a shortcoming to be entrapped into a local solution depending on the initial value and Tabu length. In the Reactive Tabu Search (RTS), functions of Reaction and Escape have been incorporated which can expand the search space more and enable to avoid the loop of search is described to the following [4,9].

### 3.2.1 Reaction Mechanism

As the Tabu length has considerable on influence the search efficiency in the TS, it necessary to choose the Tabu length properly in accordance with the target of the problem. However RTS has the function that control Tabu length automatically as follows:

- Store all solutions that have been visited,
- Extend Tabu length when Current solution has already been searched, and
- Shorten Tabu length if solution that has already been searched does not appear for a long term.

### 3.2.2 Escape Mechanism

In case that the new obtained search solution has already been search, the random search is carried out repetitively and the efficiency of searches is improved by changing the search space completely.

Fig.4 shows the concept of reaction function and Fig.5 shows a flow chart of RTS solution.

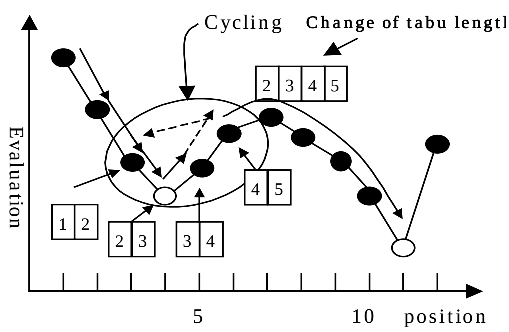


Fig.4 Function of reaction in RTS

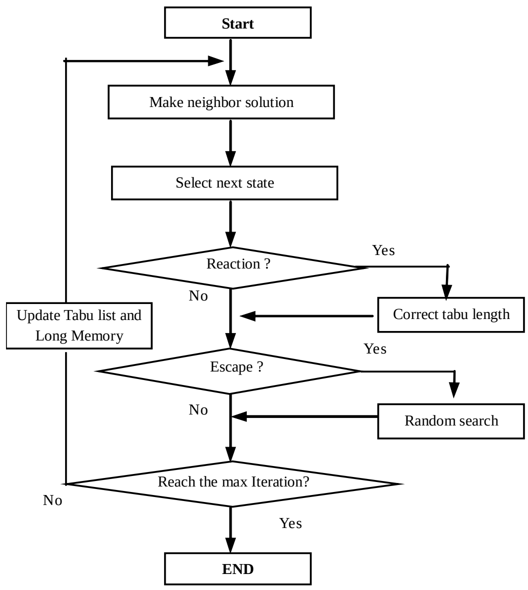


Fig.5 A flow chart of RTS

# 4 Features of Backward Forward Sweep Method

## 4.1 Features of radial structured distribution systems

Distribution systems are typically composed with the radial structure. Because of the feature of these distribution system structures, conventional power-flow methods which are mainly developed for transmission system studies are not adequate. Therefore several power flow calculation methods for the radial distribution system are proposed up to now [2,6]. In this study, the Backward Forward Sweep method is adopted for the load flow analysis [3].

Fig.6 shows a basic structure of radial distribution networks. State variables at the receiving end can be expressed by the state variables at the sending end on a single feeder as follows:

$$P_{k+1} = f_p(P_k, Q_k, |V_k|^2) \quad (4)$$

$$Q_{k+1} = f_Q(P_k, Q_k, |V_k|^2) \quad (5)$$

$$|V_{k+1}|^2 = f_{v2}\left(P_k, Q_k, |V|^2\right) \quad (6)$$

## 4.2 Power flow equations and constraints

Considering the above-mentioned relation between the up-stream (sending) and down-stream (receiving) nodes on single feeder, the rest of state variables can be calculated recursively from the source node to the end nodes by selecting the injection power to the main feeder as a state variable.

Because there is no injection power from the end of a feeder in the radial structured systems, the power flow equations for general distribution networks can be expressed as follows:

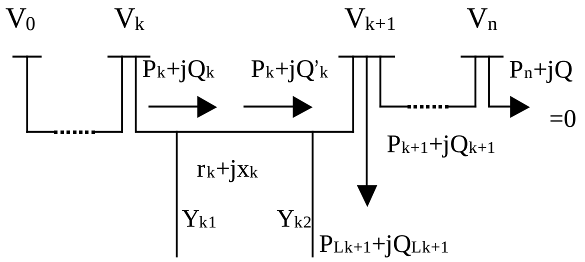


Fig.6 Basic structure of radial distribution networks

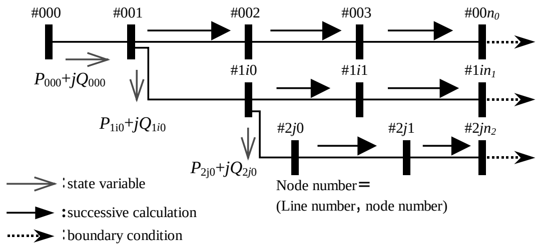


Fig.7 A general radial distribution system

$$
\begin{aligned}
&P_{ijn_{ij}} = P_{ijn_{ij}}(X_{000}, \ldots, X_{ll_m 0}, |V_{000}|) = 0 \\
&Q_{ijn_{ij}} = Q_{ijn_{ij}}(X_{000}, \ldots, X_{ll_m 0}, |V_{000}|) = 0 \\
&X_{ijk_{ij}} = (P_{ijk_{ij}}, Q_{ijk_{ij}}) \\
&i = 0, \ldots, l, \quad j = 0, \ldots, l_m
\end{aligned} \quad (7)
$$

Where, $l$: the number of level$l$,

$i_m$: the number of laterals at level $i$

$n_{ij}$: the number of nodes of lateral $j$ at level $i$.

Therefore, the above equation (8) is written by the boundary condition as follow.

$$F(X, |V_{000}|) = 0 \quad (8)$$

## 4.3 Algorithm of the convergence calculation by BFS

The nonlinear equations above can be solved using the very fast-decoupled algorithm. The correction of the state variables at each iteration can be realized by successive calculation from laterals at the highest level to the main feeder at the lowest level. The rest of state variables can be calculated by successive calculation from the source node to end of the laterals at the highest at level. The calculation repeats the backward and forward sweeps until it converges. Fig.7 shows a general radial distribution system.

# 5 Outline and Algorithm of Proposed Method

## 5.1 Proposed method of expansion planning for distribution systems

As new constructions of factories and the increase of local population etc, loads connected to the local distribution system may increase in the middle and long run. Moreover, from the view point of upper level systems, if distributed generators are installed at specific areas, loads are seemed to decrease within the distribution area. In any situations, system operators need to keep system voltages within the reference voltage range to deal with such an increase and decrease of loads. Then, an effective expansion planning method of distribution equipment is necessary to be developed and the concept of the planning can be shown as follows.

There are three types of options for the distribution equipment expansion planning as bellows;

① Change of the installation place of existing SVRs
② Increase of the number of SVRs
③ Increase of the number of SVCs

The cost becomes higher sequentially from ① to ③. Therefore, the cost of increasing the number of SVCs is the highest.

## 5.2 Tap tuning of SVRs

When determining the locations of SVRs, it is necessary not only to decide the allocations but also to tune parameters of the controllers. The installed Step Voltage Controller (SVR) regulates the tap position to

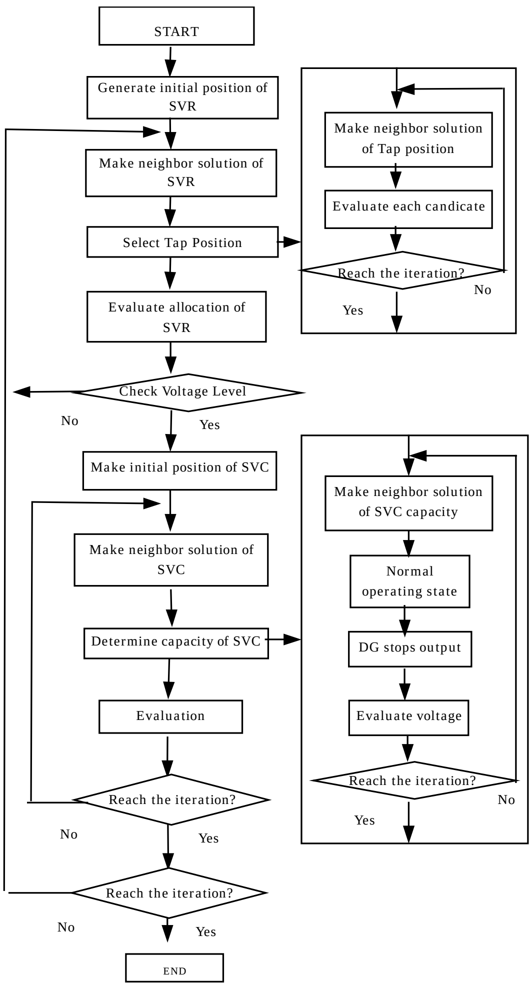


Fig.8 Flow chart of the proposed method

keep the voltage within the reference voltage range against the insertion of distributed generators. In the proposed method, RTS with multiple structures is applied for the optimal allocation. In first, the allocation candidate point and each SVR tap position are determined by minimizing the objective function in equation (1) mentioned previously. In the second, the tap positions of SVRs are optimized coordinately.

## 5.3 Determining installed capacity of SVC

Since SVCs regulate system voltages by generator or absorption of reactive powers, proper selections of the installation capacity for SVCs are critical. If SVCs with large capacity are introduced, surplus investments occur. If SVCs with small capacities are introduced, they cannot respond to steep voltage fluctuations. In this proposal method, the optimal installation capacity of SVCs is determined using RTS. It is assumed that the installation capacity of SVCs can increase by every 50kVAR from 0 to 1000kVAR. Additionally, the reactive power which is required is calculated in order to consider the voltage fluctuation in the worst case that the output of the distributed generator becomes 0.

## 5.4 Procedure of proposed method

This paper proposed the optimal coordinated allocation of both SVRs and SVCs based on Reactive Tabu Search with multiple structures. To begin with, candidate locations of SVRs are searched. Secondly, SVR's tap positions are determined. Finally, the allocation point and installation capacity are determined.

Figure 8 shows the flow of this proposal method. From this flow chart, the candidate of SVR' allocation point is searched at the beginning of this method. Then, to evaluate the effectiveness of voltage regulations by the candidate of SVR's allocation point, the optimal tap position of SVR is also determined. After that, the

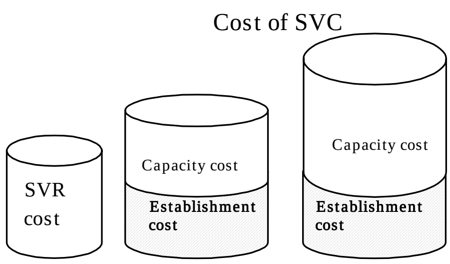


Fig.9 Configuration of cost for installing voltage equipment

voltage profile is checked. The voltages of all nodes have to be kept within the voltage reference range by SVR even if all the distributed generators stop.
When the candidate of SVRs fulfills this level, the SVC can be allocated. In the optimal allocation, the candidate of SVC allocation points is selected firstly, the installation capacity of SVC is determined secondly. In determination of installation capacities of SVCs, the voltage deviation is evaluated for the normal operation state where distributed generators produce their maximum outputs and for the outage state where distributed generator's outputs fall into zero. In other words, the SVR tap position is fixed which is determined in the normal state and necessary additional tap positions are evaluation for the outage state. Therefore the minimum installation capacity of SVCs, which can keep voltage without voltage fluctuation, is determined by RTS.
This method enables to minimize voltage deviations in normal operation state and steep voltage fluctuation state, and to allocate SVR and SVC cooperatively with the minimum investment cost. Moreover, Figure 9 shows the configuration of cost for installing voltage equipment. The installation cost of SVC is divided into the construction cost and the capacity cost. From Figure 9, the construction cost of SVC has few changes even if installation capacity is different. Then larger capacity can look cheaper in the price for each kVAR. So it is necessary to consider not only the capacity cost but also the construction cost in case of the allocation of SVC. Therefore, the total cost increases even if total installation capacity of SVC is the same capacity and the number of SVCs become increase.

## 6 Simulations on a Test System

The proposed method is applied to IEEE 34-Node Test Feeder which is modificated slightly as shown in Figure 10. This test system is assumed to have two distributed generators for the sake of simplicity. Also, it assumes that the expansion and investment for voltage control equipment are required for the original test system by reason of the increase in loads. The optimal investment for voltage control equipment is solved by the proposed RTS with multiple structures procedure. In this simulation, two 500kW-distributed generators have been installed. The number of taps of SVR is 9. The capacity of SVR is assumed to be 3000kVA.

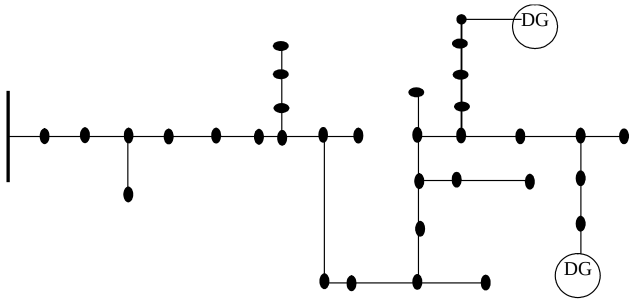


Fig.10 Standard radial distribution network

The following two different optimization approaches were adopted for examining this proposal method and making comparative studies.

CASE 1: Conventional method
In this case, SVRs and SVC are allocated separately. Additionally, in SVR allocation, the reverse power flow by distributed generators is not taken into account. In other words, it is assumed that distributed generators would not be connected to the network. After that, SVCs are allocated close to the installation points of DGs.

CASE 2: Proposed cooperative allocation method

Figure 11 and Figure 12 illustrate the result of allocation of two test cases respectively. Then Figure 13 and Figure 14 illustrate the voltage profit before and after stopping DG in each case.

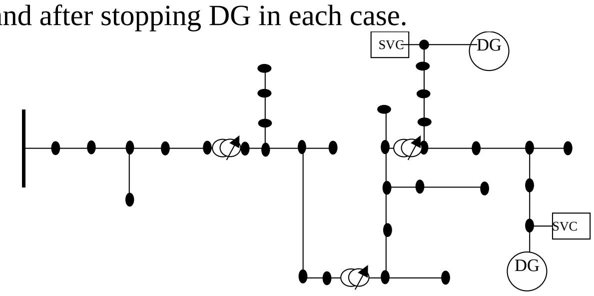


Fig.11 Allocation of SVR and SVC in CASE 1

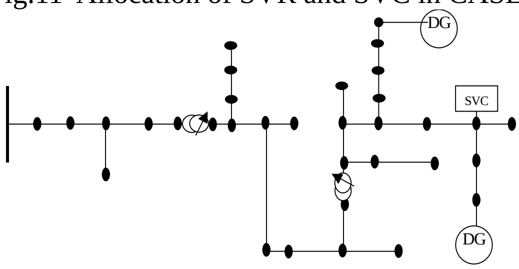


Fig.12 Cooperative allocation SVR and SVC in case 2

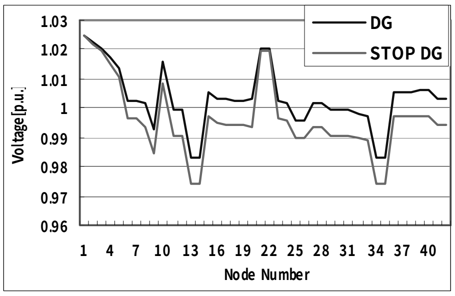


Fig.13 Voltage profile before and after stopping DG in case 1

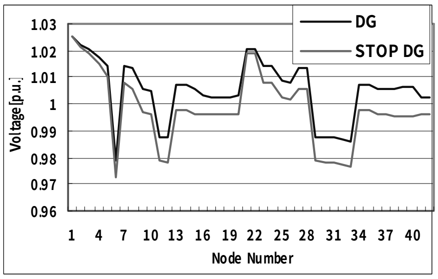


Fig.14 Voltage profile before and after stopping DG in case 2

Table 1 Comparison between case 1 and case 2

| | Case 1 | Case 2 |
|---|---|---|
| The number of SVR | 3 | 2 |
| The number of SVC | 2 | 1 |
| Total Capacity of SVC | 600kVAR | 600kVAR |

Table 1 shows the number of installation of each voltage regulators and the installation capacity of SVC in both cases. CASE 1 has three SVRs and two SVCs. CASE 2 has two SVRs and one SVC. From Figure 13 and 14, the voltage profile before and after stopping DG in each case are almost the same and can be kept within the voltage reference range. However, the number of installation of voltage regulators in case 2 can decrease compared with case 1. The proposed method enables us to decrease the number of SVR because distributed generators are installed. Moreover, though the installation capacities of each case are the same, case 2 can decrease the construction cost of SVC. From this result, it is verified the proposed method can achieve to allocate voltage equipment effectively and economically.

## 7 Conclusion

This paper proposed a coordinated allocation and control method of voltage controllers using the Reactive Tabu Search. By applying the proposed method to a practical distribution test system, it was verified that this method is efficient to allocate SVRs and SVCs at the minimum cost and regulate the system voltages within an appropriate value after introducing distributed generators into the distribution system. Also, it has been clarified that the investment cost could be reduced in case of stoppages of distributed generators and reverse power flow by distributed generators in the network.

In the future, it is important to develop more sophisticated approaches to optimize locations and installation capacities of power system controllers to regulate the voltage deviations after introducing numerous distributed generators.

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