Efficient Allocation of SVRs Optimizing the Rate of Operation for Distribution Systems

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Abstract: - An optimal allocation approach of Step Voltage regulators (SVRs) is proposed in case distributed generators are connected to distribution networks. In the proposed method, the reactive tabu search (RTS) and the enumeration method have been combined as two-step procedures. The proposed method enables us to incorporate the rate of operation of SVRs, the upper and lower limits of voltage at each node and also the upper limits of line currents as constraints. By applying the proposed method to a practical distribution test system, it has been verified that this method is efficient to allocate SVRs and regulate the system voltage within an appropriate value even after installing distributed generators into distribution systems.
Key-Words: - Expansion planning, Tabu search, SVR, Distribution system, Distributed generator

1 Introduction

Due to world–wide trends of liberalizing electric power markets and decelerations of economy, restructurings of the greater part of industries as well as electric utilities have been promoted in Japan. Conventionally, expansions of electric facilities have been undertaken by monopolized electric utilities under the embedded cost scheme, however intensive expectations have been put on profit–based construction and maintenance planning after introductions of the principal of competition into power industries.
On the other hand, distributed energy resources such as cogeneration systems have been utilized at large recently, as they have environmental friendliness, short construction periods and proximity to customers to cope with increase of future demands.
Under these circumstances, appropriate regulation of local voltages in case of installations of distributed energy resources have become a critical issue related to connections of those to distribution networks. As quality of electricity, voltages at customer ends have regulated by laws to be within a prescribed reference value, and then it is indispensable to establish more refined voltage monitoring and control approaches in the near future.
In distribution networks, the voltage control has been carried out by the Line Drop Compensation (LDC) function of the SVR (Step Voltage Regulator). SVR can be installed at banks of distribution substations and also near each feeder whenever it is required. SVRs can change their taps automatically to regulate local voltages in distribution networks, and are controlled de-centrally to keep voltages at the secondary buses respectively.
The step voltage regulators are less expensive than other devices to install, and therefore they are used in many places including Japan [1]. However, few discussions have been done on the systematic allocation of the step voltage regulators and the planning is worked out by humans. Because there are many elements to be considered in the planning, the system planners can draw up only allocation plans in the limited search region by reason of the restricted examination time. Moreover, the plans drawn by humans are not necessarily optimal.
Up to now, only negligible number distributed generators are connected to the distribution system, hence electric utilities make plans without considering the reverse power flow by distributed generators though some distributed generators are connected to the network. Therefore, as SVRs have the flexibility of being allocated in the middle of high-voltage distribution lines, for allocating those SVRs, an efficient optimal distribution system expansion planning approach has been proposed here based on the Reactive Tabu Search which is one of the meta-heuristic approaches.
Finally, the proposed method has been applied to a distribution standard test system (6,600V-system). It is verified that this approach could give the optimal

allocation of the SVRs and could also regulate the system voltages within an appropriate values after allocating the distribution generators.

2 Concept of the Rate of Operation of SVR

2.1 Feature and Model of SVR

SVRs have 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. The tap model of SVRs are formulated as follows[4].

$$Tap_k(t+1) = Tap_k(t) + r_k f_k(t) \quad (1)$$

$$d_k(t) = \begin{cases} 1 \\ 0 \\ -1 \end{cases} \quad (2)$$

$$Tap_{Low} \le Tap_k(t) \le Tap_{Upper}$$

$$k = 1,2,\cdots,N$$

where, $Tap_k(t)$: tap position of SVR k at t,
rk: change range of one step of SVR k

2.2 Formulation of Rate of Operation of SVR

As an index of evaluation, the rate of Operation of SVR is utilized for allocating SVRs effectively. The rate of Operation is an index representing the degree of contribution to voltage control of networks, and is represented as behavior of tap of SVRs for responding load change. The rate of Operation of SVR is formulated as equation (3).

$$OR_i = \int_0^T \left| Tap(t) - Tap_{Neut} \right| dt \quad (3)$$

where, OR: the Rate of Operation, Tap_{Neut}: the ratio of tap at neutral position ($Tap_{Neut} = 1$).

Fig.1 shows an example of operation of a SVR. The area of operation based on tap position 5,which means the ratio of tap is one, can express the rate of operation of each SVR in Fig.1. In other words, the rate of operation becomes 0 when tap position is fixed at tap position 5 constantly, and the contribution of the installed SVR will not be expected. Table 1 shows the voltage controllers tap positions and tap ratios and the step size of the tap changes is assumed to be 1.25%.

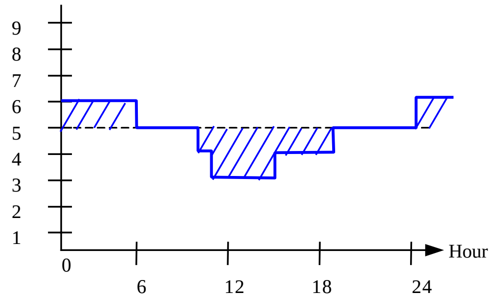


Fig.1 An example of operation of SVR

Table 1 Tap position and Tap ratio

1	2	3	4	5	6	7	8	9
95.0	96.25	97.5	98.75	100	101.25	102.5	103.75	105

2.3 Evaluation of Rate of Operation by Fuzzy Theory

In expansion plannings, the number of installation of SVRs can be determined by each rate of operation of SVRs. It is necessary to evaluate the degree of satisfaction for each rate of Operation of SVRs, hence the satisfaction rating is formulated using fuzzy function as follows.

$$\mu_k = Min\left[1, Max\left\{0, \frac{OR_k - OR_{\min}}{OR_{\max} - OR_{\min}}\right\}\right] \quad (4)$$

$$k = 1,2,\cdots,N$$

where, $OR_{\max}$: maximum satisfactory rate, $OR_{\min}$: minimum satisfactory rate.

Fig.2 shows the concept of fuzzy theory that is utilized for evaluating the rate of operation of SVRs. From Fig.2, the evaluation value becomes 0 when the rate of operation is smaller than OR_{min}, and the evaluation value becomes 1 when the rate of operation is bigger than OR_{max}. Moreover, the integrated satisfaction rating is calculated by equation (5).

$$\mu_{OR} = \prod_{k=1}^{N} (\mu_k) \quad (5)$$

From equation (5), the rate of operation of SVRs is evaluated as the satisfactory rate of installation of SVRs.

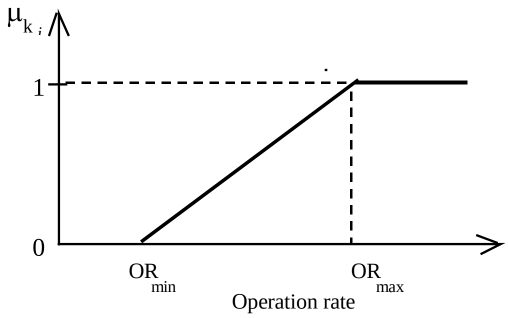


Fig.2 Membership function for voltage profile

3 Formulation of Optimal Allocation

In this distribution expansion planning, the purpose is to maximize the rate of operation of SVR and minimize to keep voltage within the prescribed value. It enables us to allocate the voltage control equipment more effectively to allocate SVRs. The object function of the optimal allocation can be formulated as follows:

Maximize

$$f = w_1 \cdot \mu_{OR} - \sum_{i=1}^{T} \left\{ w_2 \sum_{j=1}^{n} (V_j - V_{ref})^2 + w_3 \sum_{k=1}^{m} g(V,I) \right\} \quad (6)$$

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,

T: the number of time series data

n: the number of nodes

m: the number of nodes of constraint violation

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

The upper and lower limit of voltages:

$$V_{ref} - V_{band} \le V_i \le V_{ref} + V_{band} \quad (7)$$

where, V_{band}: permissible range of voltage.

Power flux upper limit on transmission lines:

$$I_{ij} \le I_{ij}^{\max} \quad (8)$$

where, I_{ij}^{max} : upper limit of current at each line.

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 maximize a multi-attribute objective function as shown in the equation (6), for optimizing the number and locations of SVRs, fulfilling the constraints on voltages and currents. It will be solved using the Back and Forward Sweep (BFS) method [2,3].

4 Procedure of Reactive Tabu Search

4.1 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 [5,6,7,9].

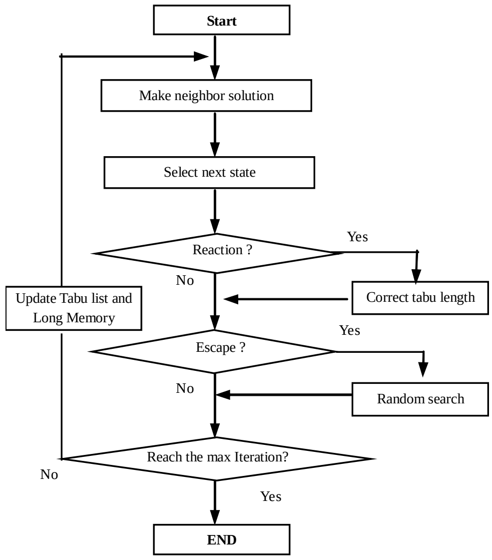


Fig.3 Flow chart of RTS

4.2 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 [8].

4.2.1 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.

4.2.2 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.3 shows a flow chart of RTS solution.

5 Outline and Algorithm of Proposed Method

5.1 Proposed Method of Expansion Planning for Distribution Systems

For the optimal allocation of SVR, which is one of the practical voltage controllers, it is necessary not only to

determine the allocation points effectively but also to tune SVR parameters appropriately.
Supposing the insertion of distributed generations, the installed Step Voltage Regulator adjusts the tap position to keep the voltage within the reference voltage range. Additionally, when plural SVRs are installed, it is indispensable to control all the SVRs coordinately and cooperatively.
In the proposed method, the allocation candidate sites and allocated SVRs tap positions are determined maximizing the objective function in equation (6).
In these two problems, different state variables are to be treated. One variable is the installation of SVR (that is, X= 1 or 0) at allocation points, the other is the tap position. It is not easy task to solve these two problems at the same time. Therefore, the state variables are selected separately concerning the controller allocation problem and the parameter tuning problem.
Fig.4 shows an example of searching process of the RTS. Creations of neighborhood solutions for the next SVR installations are shown in Fig.4, and the created neighborhood solution is evaluated.
It is necessary first to tune parameters of SVRs simultaneously with the determination of the allocation points. However it takes a lot of time to optimize the tap position for all the SVRs coordinately even after the candidate positions have been selected. Therefore, to reduce the computational time of the optimization, we have proposed an efficient approach named "voltage control area method" to identify the effect of voltage control using the sensitivity of voltage variation and also a decision method of tap positions based on the enumeration method for selecting SVRs taps.

5.2 Voltage Control Area Decision Using Voltage Variation Sensitivity

Each SVRs tap position has to be selected optimally for evaluating a candidate point of the SVR allocation.

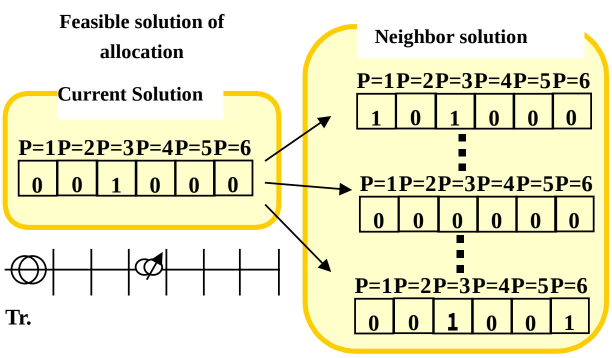
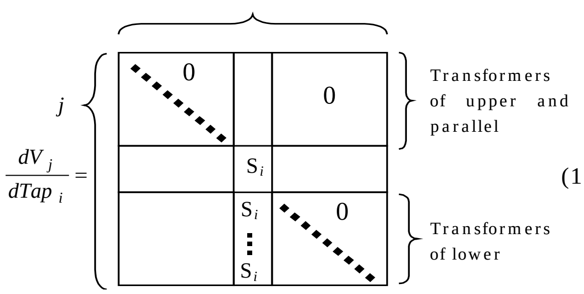


Fig.4 An example of searching process of RTS

In this proposed method, the tap position is controlled to keep the voltage at each monitored point within the reference voltage range. In selecting each voltage monitoring point to regulate the voltage at the point efficiently, the area in which a specific SVR can control the voltage is identified by using the voltage sensitivity method. Equation (9) expresses the definition of voltage sensitivities that represents the degree of voltage changes with respect to the change of one tap position.

$$S_i = \frac{V_{i(after)} - V_{i(before)}}{Tap} \tag{9}$$

A voltage variation sensitivities hold some features in distribution systems, since distribution systems are typically composed as a radial structure and there is no revers power flow by distributed generators. One of particular feature is that the influence upon another node located on a upper stream of a targeted SVR is not received. Another is the voltage variation sensitivity of the node located on the down stream becomes same level as the target node. From these feature, after the voltage variation sensitivitiy S_i of node i is caluculated, the voltage sensitivity of the node on dowen stream from node i is substituted by S_i. That is the voltage variation sensitivity of i th row can be approximated to equation (10).



(10)

In addition, it is possible to approximate by the direction of the current even if there is a reverse power flow. The effective control area can be determined by the value of sensitivity. It is necessary to restrict a node voltage of wide area more than the necessity is not influenced to control the particular node voltage, thereby the voltage sensitivity for determining effective control area is formulated as follows:

$$R_i = \frac{1}{n_i} \times \frac{dV_i}{dTap_i} \tag{11}$$

Where, n_i:t he number of nodes influenced by SVR_i
By this voltage sensitivity method, the controllable area of each SVR can be determined and the tap position also can be selected. Fig.5 shows the control

areas that have been classified by using this voltage node sensitivity method.

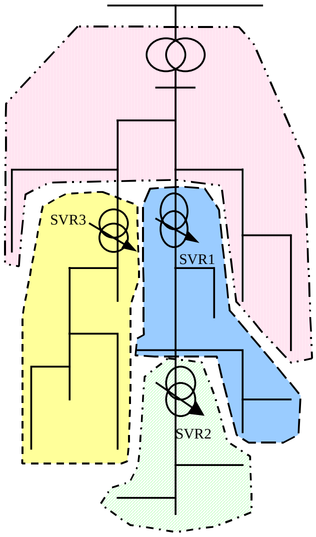


Fig.5 Controlled voltage area classified by voltage sensitivity method

5.3 Tap Tuning of SVRs

After determining the voltage control area by using the voltage control area sensitivities, each tap position is determined by the evaluation function shown as equation (12). Here, each SVR tap position is determined from up streaming (the sending end) to down streaming (the receiving end) successively, using an enumeration method, and each evaluation area of SVRs is classified by using the voltage control area sensitivities.

$$h_l = \min\left[\sum_{n=1}^{N_l}\left[(V_n - V_{ref})^2 + g(V, I)\right]\right] \tag{12}$$

where, h: evaluation functions of each volage control area, N: the number of nodes at each voltage control area, *l*: the voltage control area number

Here, we describe the procedure of the proposed method in detail. Firstly, initial solutions, which are initial installation points of SVRs, are decided at random, and neighborhoods are made from initial solutions. Secondly, at each neighborhood the controlled voltage area is classified by voltage variation sensitivity, which represents the degree of voltage changes with respect to the change of one tap position.

Next, the tap positions of SVRs are decided by using an enumeration method to keep the voltage of all nodes within the reference voltage range at each time, here the evaluation responded to a load change is carried out to evaluate the operation of SVR. However, it takes too long time to calculate system states every 24 hours. Therefore, we assumed two typical states, which are heavy load in the daytime and light load in the nigh, in this paper.

Finally, the neighborhood which is largest evaluation value is selected, and the current solution is updated. These processes are repeated till the maximum number of iteration.

6 Simulations on a Test System

The proposed method is applied to IEEE 34-Node Test Feeder which is modified slightly as shown in Fig.6. 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 method. In this simulation, two 400kW-distributed generators (DGs) have been installed. The number of taps of SVR is 9. Table 2 shows the total loads and power factors of loads in two states which is light load case and heavy load case.

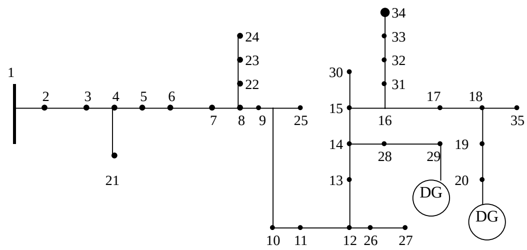


Fig.6 Standard radial distribution network

Table 2 Heavy and light load states

	Heavy	Light
Total Load [MW]	3.26	1.50
Power factor of loads	0.908(lag)	0.875(lead)

Fig.7 illustrates the result of allocation of this test system. Then Fig.8 and Fig.9 illustrate the voltage profit with and without SVRs in heavy load and light load respectively.

In generally, it is prescribed that voltages should be within 0.96-1.04[P.U.] in distribution systems. Some voltages are under 0.9[P.U.] in heavy states, and some voltages are upper 1.04[P.U.] in light states because of reverse power flow by distributed generators. From these results, the proposed method enables us to control voltages within the reference voltage range. Table 3 shows the satisfactory rates for each number of

SVRs. When the number of installed SVRs is 1 or 2, the satisfactory rate is 1 which is the maximum of the degree of the satisfaction. However, in those cases the voltages cannot be kept adequately when distributed generators are stopped. Therefore three SVRs is the optimal number of installations.

From these results, it has been verified the proposed method can achieve to allocate the voltage regulating equipment effectively.

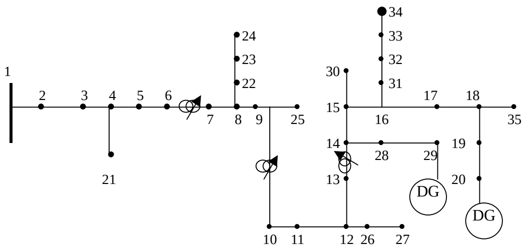


Fig.7 Allocation result of SVRs

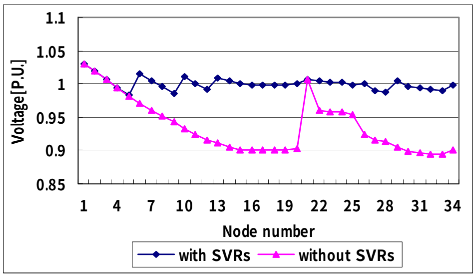


Fig.8 Voltage profile with and without SVR in heavy load state

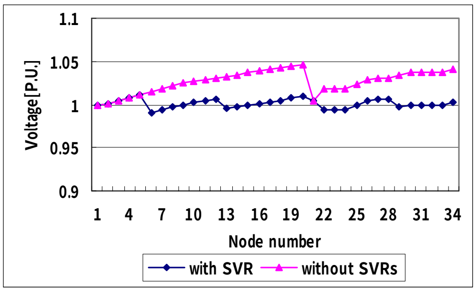


Fig.9 Voltage profile with and without SVR in light load state

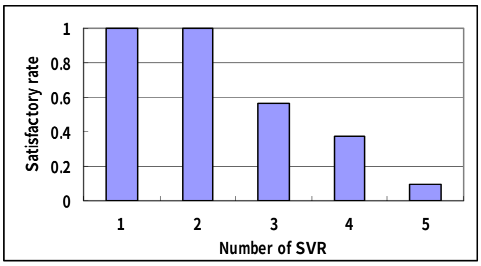


Fig.10 Satisfactory rates for each number of SVRs

7 Conclusion

An optimal allocation method of Step Voltage regulators (SVRs) has been proposed in case distributed generators are connected to distribution networks. In the proposed method, the reactive tabu search (RTS) and the enumeration method have been combined as two-step procedures. Moreover, the rate of Operation is introduced to allocate SVRs effectively. By applying the proposed method to a practical distribution test system, it has been verified that this method is efficient to allocate SVRs at the maximum rate of operation of SVR and regulate the system voltages within an appropriate value after introducing distributed generators into the distribution system.

References:

[1] T. Oomori, T. Genji, T. Yura, S. Takayama, Y. Fukuyama, "Fast Optimal Setting for Voltage Control Equipment Considering Interconnection of Distributed Generators", *Proc. of IEEE T&D Conference and Exhibition* - Asia 2002.

[2] H.D.Chiang, "A decoupled load flow method for distribution power networks: algorithms, analysis and convergence study, *Electrical Power & Energy Systems*, Vol.13, No.3, June 1991.

[3] Y. Fukuyama, H. D. Chiang, et al., "Parallel Power Flow Calculation in Electric Distribution Networks", *Proc. of IEEE ISCAS* 1996.

[4] N.Yorino, T.Fujimura, K.Uena, H.Sugihara, Y.Nakanisi, "On Autonomous Decentralized Control of On-Load Tap-Changers",T.IEE Japan, Vol.118-B, No.6, 1998

[5] K.Y.Lee and M.A. EL-Sharkawi, "Modern Heuristic Optimization Techniques with Applications to Power Systems' *New Intelligent Systems Technologies Working Group.*

[6] F.Glover, "Tabu Search Part Ⅰ", *ORSA Journal of Computing*, Vol.1, No.3, Summer 1989.

[7] F.Glover, "Tabu Search Part Ⅱ", *ORSA Journal of Computing*, Vol.2, No.1, winter 1990.

[8] R.Battiti, "The Reactive Tabu Search", *ORSA Journal of Computing*, Vol.2, No.2, pp.126-140 1994.

[9] H.Magori and R.Yokoyama, "On the Model and Solution Methods for Multi-Facility Capacity Expansion Problem", *T.IEE Japan*, 123-B, pp.1567-1572 (2003)