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Optimal Setting for Distribution Voltage Control Considering Interconnection of Distributed Generators

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1. Introduction

Distribution system voltage is regulated with transformers with automatic tap changer installed in substations and those installed in distribution feeders, which are called step voltage regulator (SVR) in Japan. Considering various load changes in practical distribution systems, parameter setting for transformers with the line drop compensation (LDC) function at substations and SVR in distribution systems is one of the important tasks in distribution control centers. The parameters for the transformers include a reference voltage and a dead band value for the reference voltage. The SVR parameters include a reference voltage, a dead band value for the reference voltage, and impedance (r+jx) for specifying the target regulated point in the target distribution systems. The setting has been performed using a heuristic equation considering the lightest and heaviest loading conditions in the target distribution system. Considering deregulation environment and introduction of distributed generation, the conventional setting method is not appropriate any more and the new setting method should be developed.

This paper presents a new parameter setting method for the transformers and SVRs with LDC functions considering interconnection of distributed generators. The proposed method can generate sub-optimal parameters setting considering various loading conditions and power output of distributed generators. Coordination of the parameter setting for the transformers and SVRs should be considered. Therefore, considering various loading conditions and the number of parameters for transformers and SVRs, the target problem can be formulated as a large combinatorial optimization problem. The objective function is to minimize the difference between a predetermined target voltage and calculated voltages at several nodes, and to minimize losses in the target distribution system. The method considers upper and lower limit of voltage at each node and upper limit of current at switches and lines as constraints. The method utilizes a reactive tabu search and an enumeration method for optimization tools. The reactive tabu search narrows the appropriate parameter ranges at the first stage. At the second stage, the method optimizes the parameter setting using multi-stage enumeration method. The feasibility of the proposed method is demonstrated on practical distribution system models with promising results.

2. Formulation of Optimal Setting Problem

2.1 Available data

The following data are able to obtained from actual distribution system:

(a) Setting values and setting ranges of each control equipment.
(b) Sending end current and voltage on substation.
(c) Major customer's contracted load value at each load section.
(d) Line type and distance (impedance) at each load section.

The each load value is able to calculated using a ratio of each load value to the total load of the target network.

2.2 State Variables

The following control equipment is considered in the optimal setting problem. The parenthetic values are setting steps.

(a) Transformer with LDC functions at the secondary side bus of Substation (S/S)
- Reference voltage; 100.0-120.5 [V] <0.5 [V]>
- Dead band value; ±1.0-±4.0 [%] <0.2 [%]>

(b) SVR with LDC functions
- Reference voltage,
  Rough setting; 95.0-115.0 [V] <5.0 [V]>
  Fine setting; 0.0-4.5 [V] <0.5 [V]>
- Dead band value; ±1.0-±4.0 [%] <0.5 [%]>
- Impedance , Rough setting; 0.0-20.0 [%] <5.0 [%]>
  (r, x) Fine setting; 0.0-4.0 [%] <1.0 [%]>

Using the above variables, one solution can be composed of a combination of setting values of each equipment. The setting values of each control equipment are set using discrete values. Therefore, the optimal setting problem can be formulated as a combination optimization problem using the discrete variables.

2.3 Objective Function

One of the important points of evaluation of optimality is to keep each section voltage within the permissible range. Therefore, it is necessary to consider minimization of the deviation of each section voltage from a certain reference voltage. Moreover, it is also necessary to consider minimization of power losses.

Consequently, the object function can be formulated as follows:

$$f_c = \min\left[\sum_{t=1}^{l}\left[w_1\sum_{i=1}^{m} Loss_i + w_2\sum_{j=1}^{n}\left(V_j - V_{ref}\right)^2 + w_3 g(V, I)\right]\right] \quad (1)$$

where, l : the number of target loading conditions,
m : the number of branches,
$Loss_i$: power loss at branch j,
n : the number of nodes,
V_j : voltage at node i,
V_{ref} : reference voltage,
W_k : weighting factor at each argument,
g(V,I) : total amount of departure from voltage and current constraint.

Subject to

(a) Voltage constraint

Voltage magnitude at each node must lie within its permissible range.

(b) Current constraint

Current magnitude at switches and lines must lie within its permissible range.

Voltage and current can be calculated by first distribution power flow (Backward-Forward sweep method [1])

3. Overview of Optimal Setting Method

3.1 Characteristic of Optimal Setting Problem

Fig.1 shows properties and solution methods for the optimal setting problem. Evaluation values in the optimal setting problem are calculated using the voltage profile and the power flow condition as shown in fig.1. The setting value of the voltage control equipment is related to the evaluation value through the tap position. Namely, the problem is a kind of inverse problem. Using voltage profiles and power flow conditions obtained as a calculation result, setting values of each equipment, which is a cause of the result, has to be determined. Several sets of setting values may have the same evaluation values when a certain section voltage is comprised within the dead band value or SVR tap position can not be actuated because of reverse power flow from distributed generators. Namely, one setting value can not be calculated using SVR tap position. Several modern heuristic methods can not be utilized for this problem because the methods select solutions with a best evaluation values in searching process. Consequently, only the enumeration method can obtain the optimal setting values. As the number of control equipment increases, the number of solutions (combinations of setting values) increases exponentially. For example one SVR has 218750 combinations and two SVRs has about 48 billions combinations. Therefore, setting for optimal setting values of multiple control equipment using a enumeration method is difficult. Setting for optimal setting values of multiple control equipment requires to narrow setting ranges using a certain method. This paper proposes a new setting method using RTS and multi-stage enumeration method for this purpose.

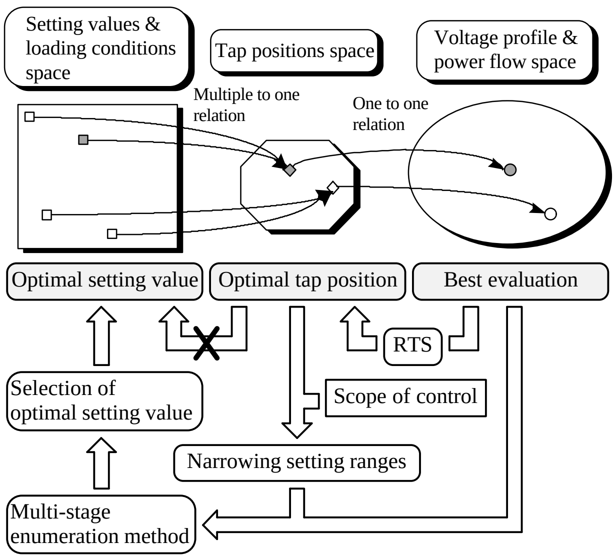

Fig.1 Concept of solutions for the optimal setting problem.

3.2 Narrowing Methods of Setting Ranges

The setting ranges of impedance and reference voltage of voltage control equipment can be narrowed considering target network area of each control equipment.

(a) Narrowing method of impedance setting ranges

The voltage control equipment controls from the equipment installation point to another equipment or end of the target feeder. The setting range of impedance can be narrowed considering line impedance at target network area of each control equipment.

(b) Narrowing method of reference voltage setting ranges

Evaluation values are calculated using the voltage profile at a certain tap position and the power flow condition as shown in fig.1. Evaluation values and tap positions are one to one relations. The optimal tap position can be obtained using RTS. The setting range of reference voltage can be narrowed considering the voltage profile at target network area of each control equipment. The following algorithm is the narrowing method of reference voltage setting ranges.

Step.1 Searching the optimal tap position

The optimal tap position minimizing of evaluation values of eq. (1) can be obtained using RTS.

Step.2 Narrowing reference voltage setting ranges

The voltage profiles at target loading conditions are determined by the optimal tap position. The reference voltage setting ranges can be narrowed considering bounds of the voltage profile at target network area of each control equipment.

Fig.2 shows an example of narrowing setting ranges at maximum and minimum loading conditions.

3.3 Multi-stage Enumeration Method

State variables and evaluation values in the optimal setting problem are multiple to one relations. The optimal setting vales can be obtained using the enumeration method. However, it is difficult to obtain the optimal setting values of multiple

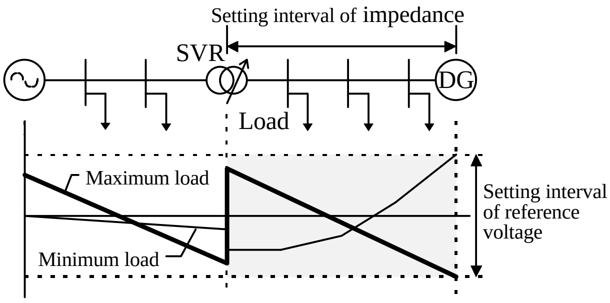

Fig.2 An example of narrowing setting ranges.

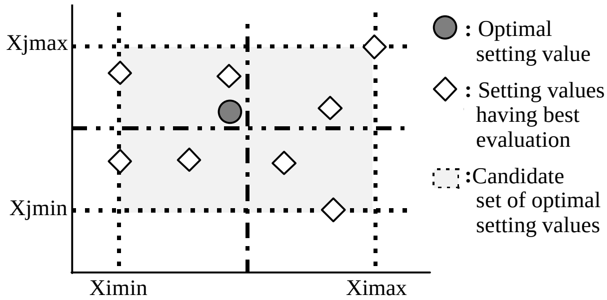

Fig.3 Concept of selecting the optimal solution.

control equipment by the enumeration method considering practical calculation time. This paper develops the multi-stage setting method using the enumeration method and adjusted setting steps. The global optimal solution may not be obtained by the proposed method. However, it can realize more effective search than a one-stage (usual) enumeration method. The following algorithm is the optimal setting method using multi-stage enumeration method.

Setp.1 Reduction of combinations of the setting values including a set of the rough optimal solutions:

The enumeration method is applied to reduce the setting ranges, which include a set of the rough optimal solutions, using the narrowed setting ranges with rough setting steps.

Step.2 Searching the candidate set of the optimal solutions:

The second stage enumeration method is applied using the reduced setting values by step 1 with the minimum setting steps. The step generates a set of the optimal solutions which minimize the objective function of the target problem.

The multiple to one relation between the setting values and the evaluation values leads to a set of the optimal solutions. Therefore, a certain method is required to determine one final optimal solution as shown below.

3.4 Selective Method of Final Optimal Setting Value

One final optimal solution (one combination of setting values) can be selected using the following equation:

$$J = \min\left[\sum_{i=1}^{n}\left[(X_{i\max} - X_i)^2 + (X_i - X_{i\min})^2\right]\right] \qquad (2)$$

where, n : the number of State Variables,

X_i : setting values having best evaluation,

X_{imax} : maximum value of setting values having best evaluation,

X_{imin} : minimum value of setting values having best evaluation.

Fig.3 shows concepts of selecting the optimal solution.

4. Numerical Examples

4.1 Simulation Condition

The proposed method is applied to a distribution model system as shown in fig.4. The model has one DG and two SVRs. SVR automatically changes tap position to regulate the voltage at a target point in distribution systems. The length of the feeder is 10.5 [km]. DG capacity is 2000 [kVA]. Table 1 shows the target loading conditions. Voltage profiles calculated with the conventional setting values and the optimal setting values are compared.

4.2 Simulation Results

Table 2 shows reduced setting ranges by the proposed narrowing method. The two-stage enumeration method is applied using the narrowed setting ranges. Table 3 shows the final optimal setting value calculated by the proposed method and the conventional setting value. The number of combination of the optimal setting values, which minimize the objective function, is 54745. Table 4, 5 and Fig. 5,6 shows voltage profiles using the optimal setting values calculated by the proposed method and the conventional setting values. The tables and figures indicate that the proposed method can

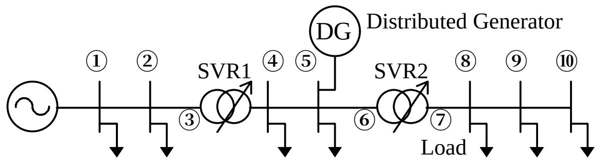

Fig.4 A distribution model.

Table 1. Target loading conditions.

	Maximum loading condition	Minimum loading condition
Total loading dose	1000[kW]	330[kW]
Power factor	Lagging 0.9	Leading -0.86
Distributed Generator	nothing	Maximum generating power
Transmission voltage	6800[V]	6600[V]

Table 2. Narrowed setting ranges.

	Setting values	Narrowed ranges
S	Reference voltage [V]	109.0～115.0
V	Dead band [%]	±1.0～±4.0
R	**r** [%]	0.0～9.0
1	**x** [%]	0.0～15.0
S	Reference voltage [V]	109.0～115.0
V	Dead Band [%]	±1.0～±4.0
R	**r** [%]	0.0～10.0
2	**x** [%]	0.0～10.0

Table 3. Optimal setting values of voltage control equipment.

	Setting values	The conventional setting method	The proposed setting method
SVR1	Reference voltage [V]	109.0	112.0
	Dead band [%]	±2.0	±2.5
	r [%]	6.0	5.0
	x [%]	3.0	7.0
SVR2	Reference voltage [V]	109.0	109.5
	Dead band [%]	±2.0	±1.0
	r [%]	6.0	10.0
	x [%]	2.0	1.0

Table 4. Voltage solutions at maximum loading condition.

Node	Distance [km]	Voltage [V]	
		The conventional setting method	The proposed setting method
①	0.00	6800.0	6800.0
②	0.85	6757.9	6757.9
③	2.20	6702.0	6702.0
④	2.20	6700.2	6700.2
⑤	3.95	6642.0	6642.1
⑥	7.35	6557.2	6557.2
⑦	7.35	6556.1	6638.1
⑧	8.10	6537.4	6619.7
⑨	9.45	6515.0	6597.6
⑩	10.50	6491.6	6574.4

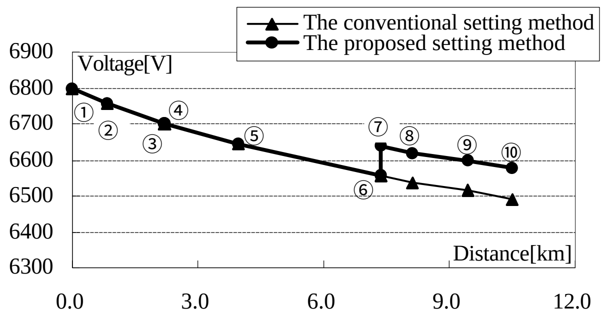

Fig.5 Voltage profiles at maximum loading condition.

modify the voltage profiles for the target loading conditions and the practical applicability of the proposed method to the optimal setting problem.

Table 5. Voltage solutions at minimum loading condition.

Node	Distance [km]	Voltage [V]	
		The conventional setting method	The proposed setting method
①	0.00	6600.0	6600.0
②	0.85	6650.7	6650.7
③	2.20	6733.5	6733.5
④	2.20	6733.7	6733.7
⑤	3.95	6845.6	6845.6
⑥	7.35	6845.8	6845.8
⑦	7.35	6503.9	6589.5
⑧	8.10	6504.0	6589.6
⑨	9.45	6504.1	6589.7
⑩	10.50	6499.9	6585.6

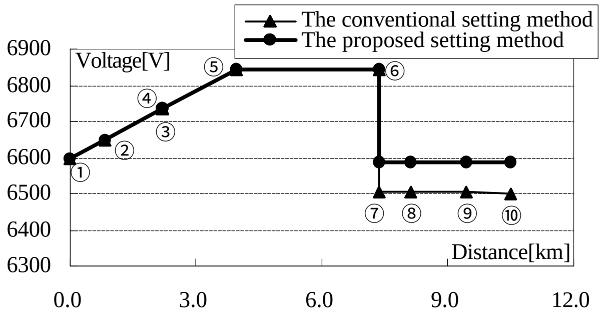

Fig.6 Voltage profiles at minimum loading condition.

5. Conclusions

This paper proposes a optimal setting method for multiple control equipment considering installation of distributed generators. The method utilizes combination of a reactive tabu search and the enumeration method as optimization tools. The proposed method has been applied to a practical model system. The results indicate that the proposed method can generate better voltage profiles for the target loading conditions compared with the conventional setting values and the practical applicability of the proposed method to the optimal setting problem.

References

[1] Y. Fukuyama, et al., "Parallel Power Flow Calculation in Electric Distribution Networks", *Proc. Of IEEE International Symposium on Circuit and Systems* (*ISCAS*), 1996.