

A CONTROL METHOD OF DISTRIBUTED GENERATORS IN SMART DISTRIBUTION SYSTEM CONSIDERING SYSTEM LOSS AND VOLTAGE

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ABSTRACT

This paper proposes a control method of distributed generators (DGs) in a smart distribution system environment, where the active and reactive power output of DGs can be actively controlled by using the communication infrastructures. In the proposed method, the power output references of DGs are determined to minimize the system loss while maintaining the bus voltages within the limits. In order to solve this nonlinear optimization problem, the sequential linear programming (SLP) method is adopted. The linearized formulation of objective function and constraints are proposed and the sensitivity matrices are modified to be applicable for this problem. The step size adjustment and convergence test method are also briefly explained. The case studies demonstrate the effects of the proposed method.

INTRODUCTION

Recently, the characteristics of the distribution system, such as the system loss and voltage, have been changed due to the increased installation of distributed generators (DGs) [1]. The DG control method based on the local control system is utilized in the present distribution system, which is a passive and radial system. However, there is a chance to more effective operation of the distribution system using DGs according to the introduction of new distribution system called “smart distribution system”, which is an active and networked system [2]. The status of the distribution system can be measured and calculated more accurately in the smart distribution system. Moreover, the power output of DGs can be controlled using the communication infrastructures. In this paper, active and reactive power output control method for DGs in smart distribution system considering the system loss and voltage is proposed. The effects of the proposed method, i.e., operation cost reduction, stability improvement, and power quality enhancement, are proven by the case studies.

DG CONTROL PROBLEM FORMULATION

The control variables of the proposed method are active (P_{DG}) and reactive power output (Q_{DG}) of DGs. The objectives of the proposed method are to minimize the system loss while maintaining the bus voltages within the limits. Therefore, with the proposed method, it is expected that the operational cost is reduced and the system stability is improved. This DG control problem

can be formulated as an optimization problem as follows.
- Minimize

$$P_{loss}(P_{DGs}, Q_{DGs}) \quad (1)$$

- Subject to

$$\begin{aligned} V_l^{\min} &\leq V_l(P_{DGs}, Q_{DGs}) \leq V_l^{\max} \\ P_m^{\min} &\leq P_{DG,m} \leq P_m^{\max} \\ Q_n^{\min} &\leq Q_{DG,n} \leq Q_n^{\max} \end{aligned} \quad (2)$$

SEQUENTIAL LINEAR PROGRAMMING

Since the relationship among the system loss, voltage, and output of DGs is highly nonlinear, the DG control problem formulated as Eq. 1 and Eq. 2 is a nonlinear optimization problem (NLP). In order to solve this NLP, we adopted a sequential linear programming (SLP) method. This method finds the optimal solution by solving a series of linear programming (LP) problem linearized at the operation point, which is determined at the previous step [3].

SLP APPLICATION TO DG CONTROL

This section describes how the SLP method can be applied to the DG control problem. The sub-functions of SLP, such as the LP formulation, step size adjustment, and convergence test method will be explained in detail.

LP Formulation

The general matrix form of the LP is as follows.

- Minimize

$$f^T X \quad (3)$$

- Subject to

$$\begin{aligned} AX &\leq b \\ lb &\leq X \leq ub \end{aligned} \quad (4)$$

where, X , lb , and ub are the vectors of decision variable, low bound, and upper bound, respectively.

Decision variable

The decision variable, X , is defined as Eq. 5 at n 'th step of SLP.

$$X = \begin{bmatrix} \Delta P_{DGs} \\ \Delta Q_{DGs} \end{bmatrix} = \begin{bmatrix} P_{DGs}^n \\ Q_{DGs}^n \end{bmatrix} - \begin{bmatrix} P_{DGs}^{n-1} \\ Q_{DGs}^{n-1} \end{bmatrix} \quad (5)$$

where, P_{DGs}^{n-1} and Q_{DGs}^{n-1} are the active and reactive power output reference calculated at the previous step of SLP, and P_{DGs}^n and Q_{DGs}^n are the reference that will be

calculated at the present step of SLP.

Linearized NLP

The objective function and constraints can be linearized as follows by applying the decision variable defined in Eq. 5.

- Minimize

$$\begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta} & \frac{\partial P_{loss}}{\partial |V|} \\ \frac{\partial P_{bus}}{\partial |V|} & \frac{\partial Q_{bus}}{\partial |V|} \end{bmatrix} \begin{bmatrix} \frac{\partial \theta}{\partial X} \\ \frac{\partial \theta}{\partial Q_{bus}} \end{bmatrix} \begin{bmatrix} \frac{\partial P_{bus}}{\partial X} \\ \frac{\partial Q_{bus}}{\partial X} \end{bmatrix} X \quad (6)$$

- Subject to

$$\begin{bmatrix} \frac{\partial |V|}{\partial P_{bus}} & \frac{\partial |V|}{\partial Q_{bus}} \\ \frac{\partial |V|}{\partial P_{bus}} & \frac{\partial |V|}{\partial Q_{bus}} \end{bmatrix} \begin{bmatrix} \frac{\partial P_{bus}}{\partial X} \\ \frac{\partial Q_{bus}}{\partial X} \end{bmatrix} X \leq \begin{bmatrix} V_i^{\max} - V_i^{n-1} \\ V_i^{n-1} - V_i^{\min} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} P_{DGs}^{\min} - P_{DGs}^{n-1} \\ Q_{DGs}^{\min} - Q_{DGs}^{n-1} \end{bmatrix} \leq X \leq \begin{bmatrix} P_{DGs}^{\max} - P_{DGs}^{n-1} \\ Q_{DGs}^{\max} - Q_{DGs}^{n-1} \end{bmatrix}$$

Sensitivity matrix

Although the form of sensitivity matrices of Eq. 6 and 7 are similar to those used in the transmission system analysis, the calculation method of some sensitivity matrices should be modified to incorporate the characteristic of the distribution system, i.e. i) the distribution system is an unbalanced system, ii) there is a mutual component in line parameter. Among the sensitivity matrices, the injection power sensitivity matrix and the voltage sensitivity matrix should be modified to reflect these characteristic.

- Injection power sensitivity matrix

The injection power sensitivity matrix represents the sensitivity between the power out of DGs and the bus injection power as shown in Eq. 8.

$$\begin{bmatrix} \Delta P_{bus} \\ \Delta Q_{bus} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{bus}}{\partial P_{DGs}} & 0 \\ 0 & \frac{\partial Q_{bus}}{\partial Q_{DGs}} \end{bmatrix} \begin{bmatrix} \Delta P_{DGs} \\ \Delta Q_{DGs} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{bus}}{\partial X} \\ \frac{\partial Q_{bus}}{\partial X} \end{bmatrix} X \quad (8)$$

The injection power sensitivity matrix is only influenced by the connection topology of the DG. The pseudo code to calculate the components of the injection power sensitivity matrix ($\frac{\partial P_{bus}}{\partial P_{DGs}} = A$, $\frac{\partial Q_{bus}}{\partial Q_{DGs}} = B$) is shown in

Table 1, where N is the number of buses, M is the number of active power controllable DGs, and L is the number of reactive power controllable DGs.

- Voltage sensitivity matrix

The voltage sensitivity matrix represents the relationship between the bus injection power and the bus voltage as shown in Eq. 9. The voltage sensitivity matrix can be calculated by taking the inverse of the Jacobian matrix of the power flow problem.

$$\begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} = \begin{bmatrix} \frac{\partial \theta}{\partial P_{bus}} & \frac{\partial \theta}{\partial Q_{bus}} \\ \frac{\partial |V|}{\partial P_{bus}} & \frac{\partial |V|}{\partial Q_{bus}} \end{bmatrix} \begin{bmatrix} \Delta P_{bus} \\ \Delta Q_{bus} \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P_{bus} \\ \Delta Q_{bus} \end{bmatrix} \quad (9)$$

Table 1. Pseudo code for calculation of the injection power sensitivity matrix

<pre> A=zeros(N, M) for i=1:1:M switch connection topology of active power controllable DG i case : single phase A(bus #, i)=1 case : two phase A(bus # 1, i)=1/2; A(bus # 2, i)=1/2 case : three phase A(bus # 1, i)=1/3; A(bus # 2, i)=1/3; A(bus # 3, i)=1/3 B=zeros(N, L) for i=1:1:L switch connection topology of reactive power controllable DG i case : single phase B(bus #, i)=1 case : two phase B(bus # 1, i)=1/2; B(bus # 2, i)=1/2 case : three phase B(bus # 1, i)=1/3; B(bus # 2, i)=1/3; B(bus # 3, i)=1/3 </pre>
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The Jacobian matrix can be calculated from the bus admittance matrix (Y_{bus}). The discriminating factor for the distribution system is the mutual line impedance. Therefore, this should be considered when calculating the bus admittance matrix. The bus admittance matrix including the mutual line impedance is calculated using Eq. 10 [4].

$$Y_{bus} = A^T [y] A \quad (10)$$

where, A is a bus incidence matrix, $[y]$ is a primitive admittance matrix.

- Loss sensitivity matrix

The loss sensitivity matrix is calculated from the Jacobian matrix as follows.

$$\begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta} \\ \frac{\partial P_{loss}}{\partial |V|} \end{bmatrix}_k = \sum_{i=1}^N J_{ik}^{11}, \quad \begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta} \\ \frac{\partial P_{loss}}{\partial |V|} \end{bmatrix}_k = \sum_{i=1}^N J_{ik}^{12} \quad (11)$$

Step size adjustment

The control variable, the active and reactive power output reference of DGs, is updated by using Eq. 12 in each step of SLP.

$$\begin{bmatrix} P_{DGs}^n \\ Q_{DGs}^n \end{bmatrix} = \begin{bmatrix} P_{DGs}^{n-1} \\ Q_{DGs}^{n-1} \end{bmatrix} + S^T X \quad (12)$$

Where, the vector S is the step size calculated from Eq. 13.

$$S_i = \begin{cases} 1 & \text{for } n = 1 \\ 0.5S_i & \text{If } \text{sign}(X_i^{n-1}) \neq \text{sign}(X_i^n) \end{cases} \quad (13)$$

Convergence test

If the maximum value of $|S^T X|$ is smaller than the predefined value, the SLP sequence is stopped.

Flow chart of the proposed method

The flow chart of the proposed method is shown in Fig. 1. Since the injection power sensitivity matrix is only dependent on the connection topology of DGs, it is calculated once in the initial step of SLP.

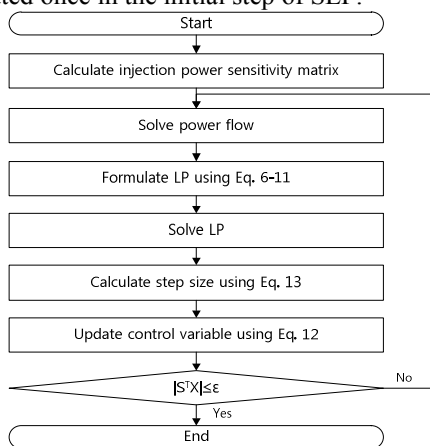


Figure 1. Flow chart of the proposed method

CASE STUDY

The proposed method is implemented as a Matlab code by utilizing the Matlab provided function “linprog” as a LP solver. The IEEE 37 node test feeder shown in Fig. 2 is used as the test system. Three DGs are installed and the information of each DG is summarized in Table 2. In order to investigate the effect of bus voltage limits, we conducted the following three cases.

- Case 1 : $V_{min}=0.97$ p.u., $V_{max}=1.03$ p.u.
- Case 2 : $V_{min}=0.98$ p.u., $V_{max}=1.02$ p.u.
- Case 3 : $V_{min}=0.985$ p.u., $V_{max}=1.015$ p.u.

Table 2. Information of installed DGs (P_0 and Q_0 : initial power output)

	Node	Phase	Active power(kW)			Reactive power(kVar)		
			Min	P_0	Max	Min	Q_0	Max
DG 1	22	a-b-c	0	400	400	-300	0	300
DG 2	23	a-b	0	100	100	-50	0	50
DG 3	34	b-c	0	200	200	-100	0	100

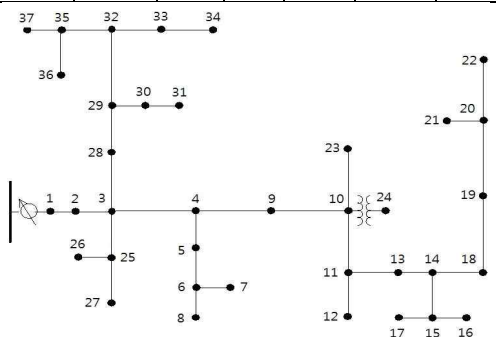


Figure 2. IEEE 37 node test feeder system

The initial system loss was 97.16 kW. The initial voltage and the voltage limits for each case are shown in Fig 3,

where the voltages of several buses are under the limits for case2 and case3.

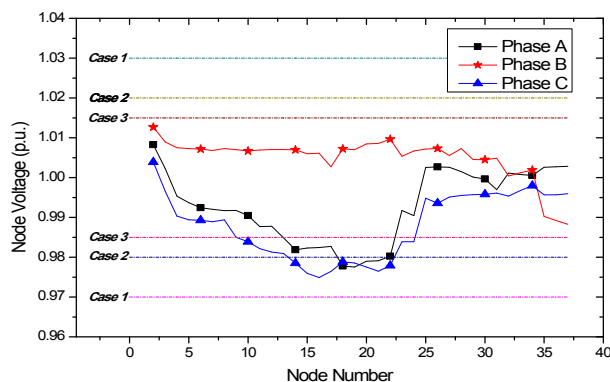


Figure 3. Initial system voltage and the voltage limit for each case

COMPUTATIONAL PERFORMANCE OF THE SLP METHOD

The performance of the proposed method was verified by comparing to the method utilizing the function “fmincon”, which is the powerful NLP solver provided in Matlab. The system loss and the calculation time are summarized in Table 3, and the calculated power references are shown in Table 4. As shown in Table 3, the power losses calculated by two methods are almost same, with maximum error less than 0.1%. We can also observe that the power references of DGs are determined accurately by the SLP method. The advantage of the SLP method is the calculation time. This method was at least 90 times faster than the function “fmincon”.

Table 3. Proposed method v.s. fmincon

Method	System loss(kW)			Time(sec)		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
SLP	78.99	85.51	89.85	1.28	3.15	1.29
Fmincon	78.96	85.51	89.77	142	285	290

Table 4. Power reference for each DG

		DG 1		DG 2		DG 3	
		P	Q	P	Q	P	Q
Case 1	SLP	400	300	100	-47	200	100
	Fmincon	400	300	100	-46	200	100
Case 2	SLP	400	238	100	-50	200	3
	Fmincon	400	243	100	-50	200	-1
Case 3	SLP	400	235	91	-50	200	-67
	Fmincon	400	233	95	-50	200	-67

Case 1

As shown in Table 3, the loss was decreased from 97.16kW to 78.99kW. In other words, by modifying the DGs power references according to the proposed method, loss can be reduced by 18.7%. The loss reduction is the largest in case1. It is because the DGs power references can be determined only to minimize the loss since there was no voltage violation in the initial state.

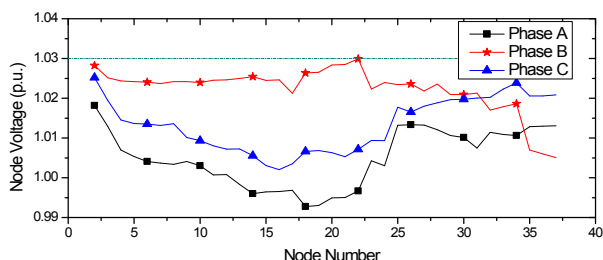


Figure 4. System voltage after applying the power reference in case 1

Case 2

As shown in Fig. 3, under voltage violation was occurred in case 2. In order to increase the system stability, this should be eliminated. If the DGs power output are not changed, the OLTC may have to change the tap position to resolve the under voltage violation. However, since the number of tap changing operation is limited, frequent tap changing will decrease its lifetime, thus increase the system operation cost. With the proposed method, under voltage violation can be eliminated with fixed tap position as shown in Fig. 5. Therefore, the proposed method can reduce the maintenance cost as well as improve the system stability.

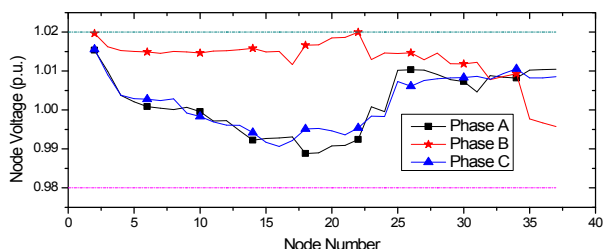


Figure 5. System voltage after applying the power reference in case 2

Case 3

In case 3, the voltage limit was assumed to be defined more tightly to provide the loads with high quality power. Similarly to case 2, under voltage violation was occurred. Since the allowable voltage range is narrow, the problem cannot be resolve only with the OLTC operation. Fig. 6 shows the bus voltages when the tap of OLTC, with step size of 1.25%, was increased by one step. Although the under voltage violation was eliminated, several bus voltages exceed the upper limits. Fig. 7 shows that by changing the DGs power output according to the proposed method, it is possible to maintain the voltages within the tight limits. This demonstrates that the proposed method can enhance the power quality of the distribution system by maintaining the voltage very close to the nominal value.

CONCLUSIONS

The sequential linear programming (SLP) based DGs control method was proposed to minimize the system loss

while the bus voltages are maintained within the limits. The DGs control problem was formulated as a nonlinear optimization problem. The linearization method with the injection sensitivity matrix, which reflects the unbalanced characteristic of the distribution system, is proposed to solve the nonlinear optimization problem using SLP. The effects of the proposed method was analysed by three case studies using different voltage limit. The advantages of the proposed method are: i) operation cost reduction by minimizing the system loss and preventing the tap change of OLTC, ii) system stability improvement by maintaining the voltage within its limit, and iii) power quality enhancement by controlling the voltage more tightly. With the proposed method, the smart distribution system can be operated more effectively.

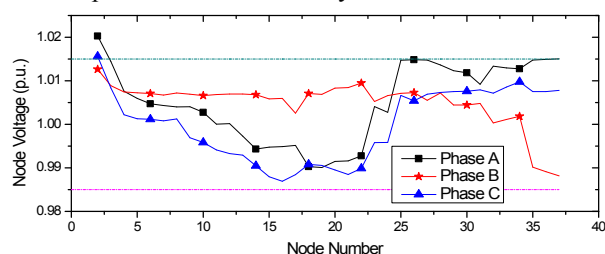


Figure 6. System voltage after tap changing in case 3

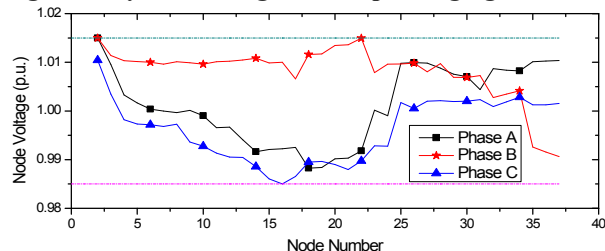


Figure 7. System voltage after applying the power reference in case 3

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