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Feeder Loop Line Control for the Voltage Stabilization of Distribution Network with Distributed Generators

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Abstract – When renewable sources are connected to the distribution network in the form of a distributed generators(DGs), the effect of intermittent output appears as voltage fluctuation. The surplus power at the consumer ends results in the reverse power flow to the distribution network. This reverse power flow causes several problems to the distribution network such as overvoltage. Application of the reactive power control equipment and power flow control by means of BTB inverter have been suggested as the general solutions to overcome the overvoltage, but they are not economically feasible since they require high cost devices. Herein, we suggest the feeder loop line switch control method to solve the problem.

Keywords: Feeder loop line control, Distributed generation, Distribution network control

1. Introduction

As the penetration of renewable sources in the distribution networks increases, distribution network operators are concerned with possible voltage fluctuation problems in the conventional tree-configured distribution network. The voltage fluctuation problem can be managed at the nodes by reactive power control devices like SVC or DSTATCOM [1-3]. BTB inverter type controller was introduced to regulate voltage by controlling power flow [4]. Energy storage system is an effective way to prevent reverse power flow. But, these solutions are too costly to be applied to the wide range of distribution networks.

Here, we introduce the define feeder loop line as the line with switching devices placed between feeders. The distribution networks can have loop configuration by switching on the loop lines.

The bus voltage at a distribution network can be controlled by controlling network configuration, i.e., by controlling on or off status of the loop lines. The distribution network can be resumed to the original tree configuration when loop line is switched off. The DGs are assumed to be connected to the distribution network of which the voltage level is 22.9 kV or less.

2. The Reverse Power Flow Problem in Distribution Network

The reverse power caused by the DG installed at the distribution network flows into the feeder as shown in Fig. 1. The voltage at the node to which DGs are connected increases as the reverse power flow increases.

Thus the node voltage may excurse over the allowed operating voltage ranges. The operating voltage ranges and voltage profile with reverse power flow from dispersed DGs are shown in Fig. 2.

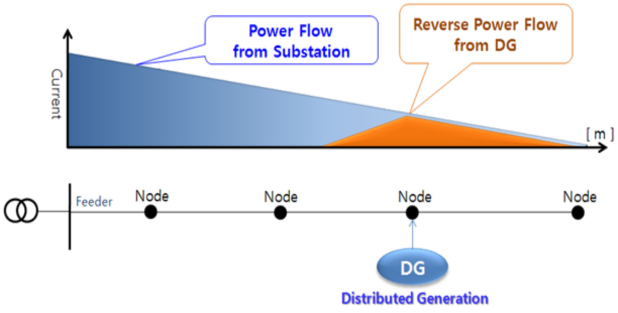

Fig. 1. The flow of the reverse power flow generated by the DG

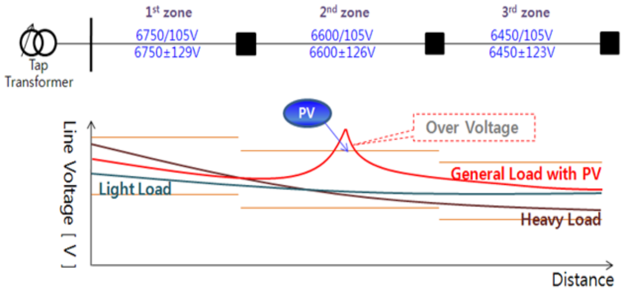

Fig. 2. Overvoltage by reverse power flow

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3. Feeder Loop Line Control

The feeder loop line control is defined as a method to control the status of the feeder loop line by switching on or off the loop line placed between the feeders. The surplus power of feeder shifted to the other feeder through the loop line. As a result, the overvoltage at the node is dropped to the normal voltage range.

3.1 The advantage of the feeder loop line

Fig. 3 shows the power loss depending on the DG output power level with the feeder loop line switched on and off, respectively.

Though appropriate DG in the distribution network reduces the power loss, an excessive DG output increases the power loss by the reverse power flow. The looped distribution network with the feeder loop line switched on can reduce the power loss as shown in Fig. 3. Fig. 4 shows the voltage evaluation index [A] defined in Eq. (2). The values of the voltage evaluation index depend on the DG's output power levels and distribution network configurations. The node overvoltage can be prevented by the looped distribution network.

3.2 The place of the loop line at the distribution network

The loop lines are placed between two feeders with the same nominal voltages, i.e. the same region. The node at feeder 1 in region i is connected to the node at feeder 2 in region i through the feeder loop line. This strategy allows the region with the feeder loop line to have the same nominal voltage level. The loop lines are not placed to connect two nodes in different regions as shown in Fig. 5.

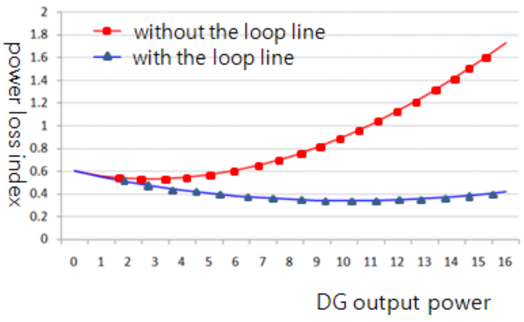


Fig. 3. The power loss index with the feeder loop line switched on and off

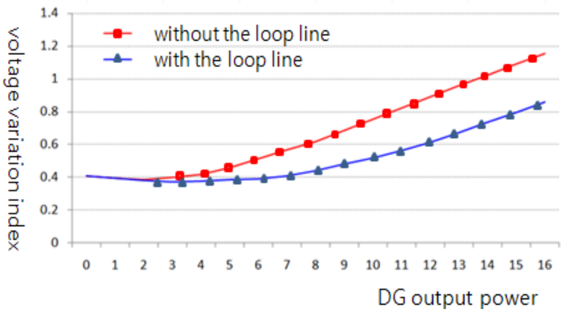


Fig. 4. The voltage variation index with the feeder loop line switched on and off

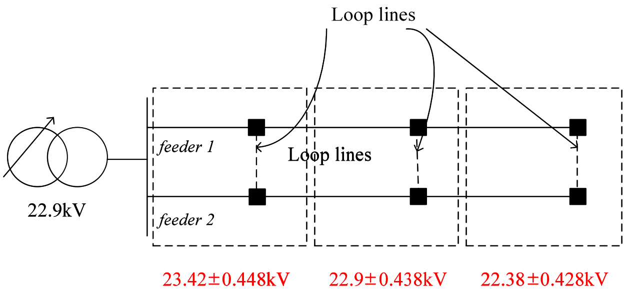


Fig. 5. Loop lines installed between the nodes with the same nominal voltages

4. Feeder Loop Line Status Control

The feeder loop lines are placed between the feeders to add power flow paths to control the voltages at the nodes to which DGs are connected. However, the feeder loop lines are not always needed to be switched on depending on the distribution network conditions. The control variables are the status of the feeder loop lines, on and/or off. If n loop lines are placed between two feeders, 2^n loop line status can be constituted. The most reasonable configuration of the networks is selected considering the power loss and the node voltage.

For the simplicity of this study, two-feeder system was chosen as in Fig. 6.

The system can be divided by regions with different nominal voltage and voltage ranges, $V_{i,nom} \pm \Delta V_{i,nom}$. Where, $V_{i,nom}\ (= V'_{i,nom})$ is the nominal voltage at region i, and $\Delta V_{i,nom}\ (= \Delta V'_{i,nom})$ is voltage deviation allowed at region i.

We assume that one loop line has been prepared at each region for looping the feeders and the region voltage is represented by the node voltage.

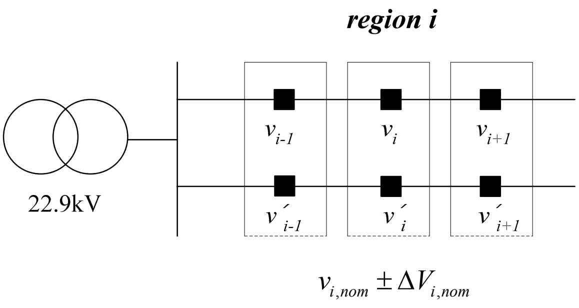


Fig. 6. Node range allocated to loop lines

4.1 The control objective for the loop line control

4.1.1 The voltage evaluation index

The voltage evaluation index [A] is defined by Eq. (1).

$$[A^I] = \frac{1}{2N}\sum_{i=1}^{N}[(\frac{\Delta v_i^I}{2\Delta V_i})^2 + \left(\frac{\Delta v'^I_i}{2\Delta V_i}\right)^2]$$

I : a set of s_k such that $s_k = 1$
s_k: the status of k_{th} loop line, (1:on, 0:off)
k= 1,2, …. K
K : number of loop lines
N : number of nodes voltages are measured (1)

where, s_k : the status of k_{th} loop line, 1 or 0

$$\Delta v_i = \left| v_i - V_{i,nom} \right| \tag{2}$$

$$\Delta v_i' = \left| v_i' - V_{i,nom}' \right| \tag{3}$$

v_i, v_i' : the voltage of region i, measured at each feeder

The voltage evaluation index is zero if the node voltage is equal to the nominal voltage and higher than 1 if the node voltage is out of the allowed operating range.

4.1.2 The power loss index

The power loss at a line of impedance Z between two nodes is given by Eq. (4).

$$P_{ij} = \frac{R\sqrt{(E_i\cos\delta_i - E_j\cos\delta_j)^2 + (E_i\sin\delta_i - E_j\sin\delta_j)^2}}{|Z|^2} \tag{4}$$

Then, the power loss at a network is approximately given by Eq. (4).

$$[B^I] = \sum_{j}^{L}\sum_{i=1}^{N_i-1} P^I_{i,i+1} + P^I_{k,ll}\cdot s_k$$

$$\mathrm{k} = 1{,}2,\ \ldots \mathrm{K}$$

L : number of feeders
$\mathrm{N_i}$: number of nodes at i_{th} feeder
$P_{k,ll}$: power loss at k_{th}loop line (5)

4.1.3 The cost function

The feeder loop line control is to determine the status of s_k so that node voltages and power losses are to be minimized.

The cost function for the control is given by Eq. (6).

$$\min_I\ sqrt(\alpha\,[A^I]^2 + \beta\,[B^I]^2)$$

for i = 1, 2,…n

where, I : a set of s_k such that $s_k = 1$

$$\boldsymbol{\alpha} + \beta = 1,$$
$$0 < \boldsymbol{\alpha} < 1,\quad 0 < \beta < 1 \tag{6}$$

The optimal distribution network is one of the 2^Kpossible configurations of the distribution networks that can be constituted by K loop lines. The simplest way to calculate the cost function is to solve power flows2^Ktimes.

6. Simulation Results

The simulation study has been carried out by using PSCAD/EMTDC software.

We assumed that the power loss at loop lines, $P_{k,ll}$, are all the same by 5 kw and that the nominal voltage of center of the feeder is 22.9kV. The operating voltage range is +/-2% of the nominal voltage. The parameters of line constants are shown in Table 1.

The loads are assumed to be distributed equally to each node throughout the feeder. In the simulation, two load cases were considered, one is heavy load case with 10 MVA with power factor of 0.9 and the other is light load case with 7 MVA with power factor of 0.9.

As shown in Fig. 8, the voltage profiles of a feeder with

Table 1. Parameters of loop line

Item	Impedance(Ω/km)	R/X ratio
Cu125mm^2	0.313+j0.338	0.926
Cu80mm^2	0.237+j0.329	0.720
Cu60mm^2	0.149+j0.314	0.475

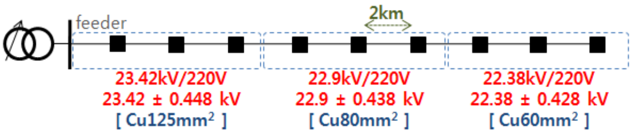


Fig. 7. Voltage ranges of a feeder

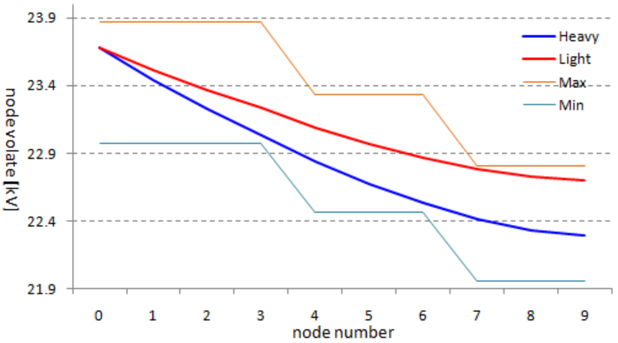


Fig. 8. Voltage profiles before DG applied.

heavy load is lower than those of a feeder with light load.

5.1 Case studies

The simulation studies for two cases were conducted. One is the case when the network consists of three heavy loaded feeders as in Fig. 9, the other is the case when the network consists of two heavy loaded feeders and one light loaded feeder as in Fig. 10.

A generation source is placed in the middle of a feeder in any cases. The influence of various output level to voltage profiles was investigated. The output levels we considered

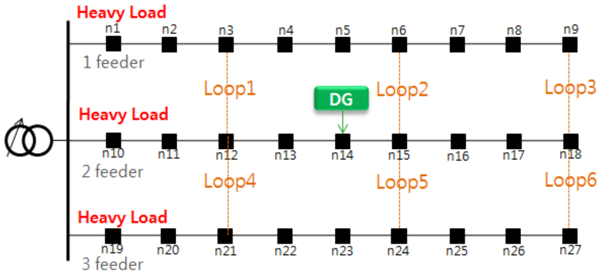


Fig. 9. Configuration of case study 1

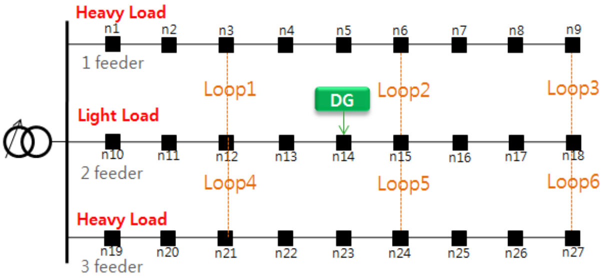
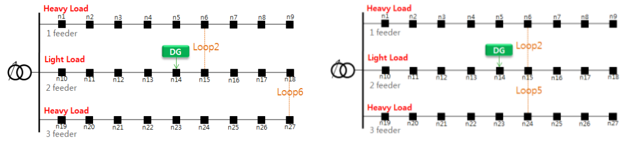


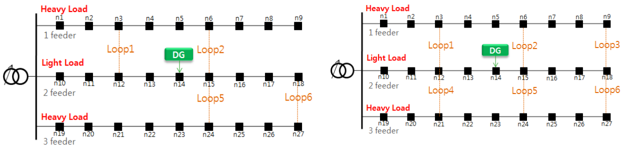
Fig. 10. Configuration of case study 2

Table 2. Result of simulation

DG[MW] \ CASE		CASE 1		CASE 2	
		Before control	After control	Before control	After control
0MW (case1) 0MW (case2) [0%]	Loop State	[x, x, x x, x, x]	[x, x, x x, x, x]	[x, x, x x, x, x]	[x, o, x x, x, o]
	A	0.21442	0.21442	0.23622	0.13862
	P_{loss}	0.70767	0.70767	0.59069	0.59157
	E	0.51822	0.51822	0.45921	0.41803
	Overvoltage node	no	no	no	no
2.1MW (case1) 1.89MW (case2) [7%]	Loop State	[x, x, x x, x, x]	[x, o, x x, o, x]	[x, x, x x, x, x]	[x, o, x x, o, x]
	A	0.18346	0.16210	0.33092	0.13727
	P_{loss}	0.62775	0.63069	0.54218	0.52471
	E	0.45694	0.45063	0.49006	0.37577
	Overvoltage node	no	no	n_{16}, n_{17}	no
4.2MW (case1) 3.78MW (case2) [14%]	Loop State	[x, x, x x, x, x]	[x, o, x x, o, x]	[x, x, x x, x, x]	[o, o, x x, o, o]
	A	0.21599	0.13424	0.47236	0.14490
	P_{loss}	0.57837	0.56077	0.51787	0.47610
	E	0.44195	0.39721	0.58508	0.34891
	Overvoltage node	no	no	n_{16}, n_{17}, n_{18}	no
6MW (case1) 5.4MW (case2) [20%]	Loop State	[x, x, x x, x, x]	[x, o, x x, o, x]	[x, x, x x, x, x]	[o, o, x x, o, o]
	A	0.28943	0.12870	0.62734	0.17030
	P_{loss}	0.55942	0.51412	0.51565	0.43861
	E	0.47208	0.36611	0.71536	0.33838
	Overvoltage node	n_{16}	no	n_{13}, n_{16}, n_{17}, n_{18}	no
9MW (case1) 8.1MW (case2) [30%]	Loop State	[x, x, x x, x, x]	[o, o, x x, o, x]	[x, x, x x, x, x]	[o, o, o o, o, o]
	A	0.49477	0.15071	0.94758	0.47795
	P_{loss}	0.57384	0.46240	0.54872	0.40112
	E	0.62542	0.34313	1.01573	0.35535
	Overvoltage node	n_{13}, n_{14}, n_{16}, n_{17}, n_{18}	no	n_{13}, n_{14}, n_{15}, n_{16}, n_{17}, n_{18}	no



(a) DG output : 0MW (b) DG output : 1.89MW



(c) DG output : 3.78MW (d) DG output : 8.1MW

Fig. 11 Simulation results (case 2)

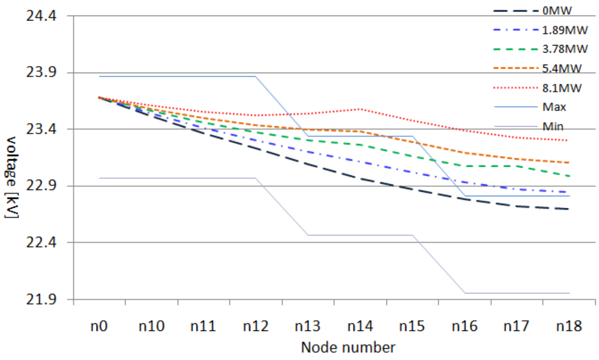


Fig. 12. Voltage profiles of case2 without control

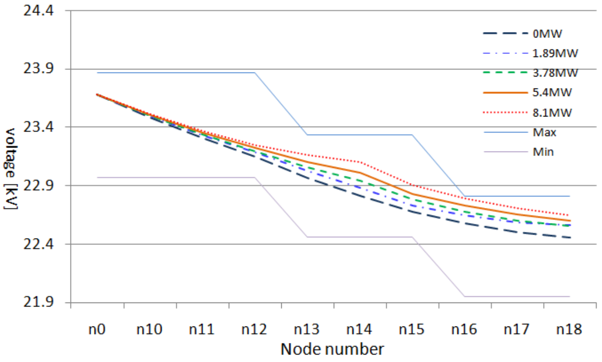


Fig. 13. Voltage profiles of case 2 with control

are 0%, 7%, 14%, 20%, 30% of the total load.

The weighting factor α and β were given 0.5 respectively.

The simulation results were summarized in Table 2. ‘o’ represents that the loop line is on status, on the other hand ‘x’ represents the off status.

When the loop line control is not applied, the number of nodes with overvoltage in case 2 are larger than that of case 1. That is why reverse power under light load is greater than the heavy load case. The voltage profiles of case 2 are shown in Figs. 12 and Fig. 13. Overvoltage over the feeder caused by reverse power flow from distributed generator has been suppressed into the specified voltage range by the feeder loop line control.

6. Conclusion

When distributed generators are included in the distribution networks, the feeder voltages tends to rise over the specified range proportionally to the output levels of the generators. The loop line control can be a solution to the overvoltage problem and reduce power losses of distribution networks. Further studies are needed to develop optimization methods to get the solutions considering taps of transformations.

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