

A DROOP CONTROL DESIGN METHOD IN DC MICROGRIDS

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ABSTRACT

The analysis and design of the droop control applied to the bi-directional distributed generator in the dc microgrid are presented. The effects of line resistance on power sharing and voltage regulation performance are analysed. In order to interpret the complicated line configuration, the voltage sensitivity analysis based on the power flow analysis is derived. Based on this analysis, a droop control design method is proposed to improve the droop control performance. The design method is implemented through an PSCAD/EMTDC simulation. In a simulation model of dc microgrid, three bidirectional distributed generators, three loads, and one non-dispatchable distributed generators are connected to the 5-bus network model, and the improved performance are verified.

INTRODUCTION

As power generation capacity of renewable energy has increased globally, research on microgrid (MG) has been carried out to utilize power effectively. Various control strategies have been proposed for stable operation of dc MGs. Conventional control strategies can be classified into centralized control, distributed control, and decentralized control. The centralized control system acquires the information of distributed generators (DGs) through the communication system, and the energy management system delivers the appropriate control command. However, this requires a high speed communication infrastructure.

In order to overcome the limitation of centralized control, distributed control and decentralized control have been proposed. The distributed control exchanges information of DGs through low-bandwidth communication and uses it to improve voltage regulation and power sharing performance [1]. This distributed control has the advantage of overcoming a single point of error in communication, but there is still a communication dependency.

Since the decentralized control performs the control only with the local information, the communication system is not necessary, and generally the droop control is used [2]. The droop gain is an important parameter

affecting control performance and stability. To achieve accurate power sharing between DGs, it is necessary to properly design the droop gain. Line resistance is a factor affecting the droop gain value and should be considered when designing the droop control.

This paper analyzes the characteristics of droop control applied to dc MG and discusses the design method of droop gain. The influence of the droop gain and line resistance on the power sharing accuracy and voltage regulation performance of DGs is analyzed. The voltage sensitivity analysis is performed through power flow analysis including droop control characteristics [3]. Based on this analysis, a droop control design method is proposed that improves power sharing performance while satisfying the voltage regulation range under maximum load and generation situations. Simulation results are provided to verify the performance of droop control and its design method.

DROOP CONTROL AND EFFECT OF LINE RESISTANCE

Droop control method

Droop control is used for power sharing between bi-directional distributed generators (BDGs). As shown in (1), the output voltage reference $v_{o,n}^*$ of the n th BDG is linearly decreased as the output current $i_{o,n}$ increases by the droop control. Where V_{nom} is the nominal voltage, and $R_{d,n}$ is the droop gain.

$$v_{o,n}^* = V_{nom} - R_{d,n} \cdot i_{o,n} \quad (1)$$

BDGs perform power sharing by taking charge of the output proportional to the rated power, where $R_{d,n}$ is determined as (2)

$$R_{d,n} = \frac{\Delta V \cdot V_{min}}{P_{rated,n}}, \quad (2)$$

where ΔV , V_{min} , and $P_{rated,n}$ represent the voltage variation width, minimum allowable voltage, and rated power of the n th BDG of dc MG, respectively.

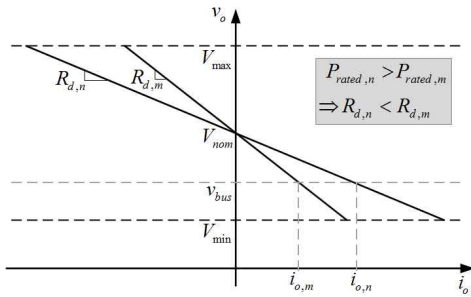


Fig. 1. Droop control characteristic curve.

Fig. 1 shows the relationship between the output voltage v_o and i_o for the n th and m th BDGs with different rated power, where v_{bus} is the dc bus voltage. As shown in Fig. 1, when $P_{rated,n}$ is greater than $P_{rated,m}$, $R_{d,n}$ is smaller than $R_{d,m}$ according to (2), whereby the n th BDG is responsible for a larger output power.

When the ratio of output power $p_{o,n}$ to $P_{rated,n}$ (denoted as p_n^{ratio}) and difference of between p_n^{ratio} (denoted as Δp_{nm}^{ratio}) can be defined as

$$p_n^{ratio} = \frac{P_{o,n}}{P_{rated,n}} \quad (3)$$

$$\Delta p_{nm}^{ratio} = \left| p_n^{ratio} - p_m^{ratio} \right|. \quad (4)$$

At the ideal case where there is no line resistance, Δp_{nm}^{ratio} becomes 0, and accurate power sharing is performed. However, practical dc MGs has line resistance, which degrades control performance.

Degraded droop control performance by line resistance

The effective value of droop gain $R_{d,n}^{eff}$ can be expressed as

$$R_{d,n}^{eff} = R_{d,n} + R_{line,n}^{eq} \quad (5)$$

where $R_{line,n}^{eq}$ is equivalent line resistance connected to the n th BDG. Since the droop gain is changed from $R_{d,n}$ to $R_{d,n}^{eff}$, Δp_{nm}^{ratio} has a value exceeding 0, which means that the power sharing accuracy is degraded. It is difficult to derive $R_{line,n}^{eq}$ when many BDGs are connected to complex line configurations.

Due to the characteristics of droop control, the output voltage $v_{o,n}$ fluctuates according to the change of $i_{o,n}$ of BDG, which affects v_{bus} . A v_{bus} decreased by the line voltage drop, and v_{bus} decreases as $i_{o,n}$ increases.

When the total load power consumption increases to a level close to the sum of the rated power of the BDGs,

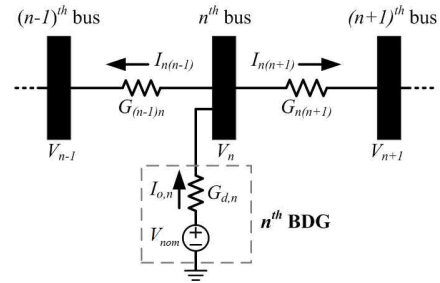


Fig. 2. Bus configuration with BDG.

v_{bus} will be lower than V_{min} and out of the allowable voltage range. Therefore, when designing the droop gain, consideration should be given to the line configuration and maximum load power so that these phenomena do not appear.

VOLTAGE SENSITIVITY ANALYSIS

Fig. 2 shows the line structure in which three buses are connected, where $G_{n(n+1)}$, $I_{n(n+1)}$, and V_n are the line admittance, line current, and n th bus voltage. $I_{o,n}$ is the output current of BDG, and $G_{d,n}$ is the reciprocal of the droop gain.

Representing the sum of the current flowing from the n th bus to the adjacent bus and the BDG as I_n , it can be generalized and the power equation of the n th bus can be derived as (6).

$$P_n = \sum_h^N G_{nh} V_n (V_n - V_h) + G_{d,n} V_n (V_n - V_{nom}) \quad (6)$$

Equation (7) express the power flow equation as linearized by the Jacobian matrix \mathbf{J} , where $\Delta \mathbf{P}$ and $\Delta \mathbf{V}$ are $N \times 1$ matrices for the power variation ΔP_n and the voltage variation ΔV_n . The component J_{nm} of \mathbf{J} can be obtained by means of partial differentiation of the bus voltage from the power equation as shown in (8).

$$\Delta \mathbf{P} = \mathbf{J} \cdot \Delta \mathbf{V} \quad (7)$$

$$J_{nm} = \frac{\partial P_n}{\partial V_m} \quad (8)$$

The voltage sensitivity matrix \mathbf{S} can be obtained by taking the inverse of the \mathbf{J} matrix as shown in (9), and the linearized $\Delta \mathbf{V}$ for $\Delta \mathbf{P}$ can be expressed as in (10).

$$\mathbf{S} = \mathbf{J}^{-1} \quad (9)$$

$$\Delta \mathbf{V} = \mathbf{S} \cdot \Delta \mathbf{P} \quad (10)$$

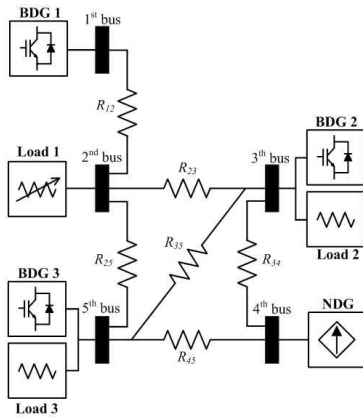


Fig. 3. Diagram of 5-bus configuration with DGs and loads.

DROOP CONTROL DESIGN METHOD

Based on the aforementioned voltage sensitivity analysis, a droop control design method is proposed. It is designed to improve the power sharing accuracy and voltage regulation performance. In the proposed method, the final droop gain $R'_{d,n}$ is calculated by multiplying original $R_{d,n}$ according to (2) by α_n and β coefficients. The detailed procedure of the droop gain design method is presented as follows.

- 1) The first step is to initialize α_n and β coefficients as 1 and calculate the \mathbf{S} for the target dc MG.
- 2) The next step is to calculate the α_n coefficients. The α_n coefficient is defined as the ratio of the voltage variation ΔV_n of the n th BDG to the voltage variation ΔV_M of the reference BDG. The α_n coefficient is expressed as the maximum load situation α_n^{load} and the maximum generation situation α_n^{gen} as follows.

$$\alpha_n^{load} = \frac{\Delta V_n^{load}}{\Delta V_M^{load}} = \frac{\sum_{h \in \{load\ bus\}} S_{nh} \cdot \Delta P_h^{load}}{\sum_{h \in \{load\ bus\}} S_{Mh} \cdot \Delta P_h^{load}} \quad (11)$$

$$\alpha_n^{gen} = \frac{\Delta V_n^{gen}}{\Delta V_M^{gen}} = \frac{\sum_{h \in \{NDG\ bus\}} S_{nh} \cdot \Delta P_h^{gen}}{\sum_{h \in \{NDG\ bus\}} S_{Mh} \cdot \Delta P_h^{gen}} \quad (12)$$

- 3) Next is to determine the β coefficient. The new droop gain $R'_{d,n}$ is calculated by using the value of α_n determined in the previous step and β is defined as (13).

$$R'_{d,n} = \begin{cases} R_{d,n}^{load} = \alpha_n^{load} \beta^{load} R_{d,n}, & (i_{o,n} \geq 0) \\ R_{d,n}^{gen} = \alpha_n^{gen} \beta^{gen} R_{d,n}, & (i_{o,n} < 0) \end{cases} \quad (13)$$

The voltage sensitivity matrix is recalculated to reflect the new droop gain; this yields the maximum voltage fluctuation values ΔV_{max}^{load} and ΔV_{max}^{gen} expressed in (14). If ΔV_{max}^{load} is larger than the predefined voltage variation width ΔV_{def} , β^{load} is decreased. This process is repeated until ΔV_{max}^{load} becomes smaller than ΔV_{def} . The same procedure is repeated for β^{gen} as well.

$$\begin{aligned} \Delta V_{max}^{load} &= \text{Max}[\Delta \mathbf{V}^{load}] = \text{Max}[\mathbf{S} \cdot \Delta \mathbf{P}^{load}] \\ \Delta V_{max}^{gen} &= \text{Max}[\Delta \mathbf{V}^{gen}] = \text{Max}[\mathbf{S} \cdot \Delta \mathbf{P}^{gen}] \end{aligned} \quad (14)$$

- 4) Finally, the final $R'_{d,n}$ is determined using α_n and β . Fig. 3 shows the dc MG configuration with DG and load connected to the 5-bus line configuration, and detailed parameter values are summarized in Table I. The new droop gain values calculated by the proposed droop control design method are summarized in Table II. The reference BDG is set to BDG 1 with the largest rated power.

SIMULATION RESULTS

In order to verify the proposed droop control design method, a PSCAD/EMTDC simulation consisting of three BDGs, three loads and one NDG was constructed. Fig. 4 shows the power sharing performance and bus voltage waveform for a load dominant situation where loads consume maximum power and NDG does not have power generation. The left part of the waveform is the result when the original droop gain is applied and the right part is the result when applying the new droop gain calculated by the proposed droop control design method. As shown in Fig. 4, when the designed droop gain is applied, $\Delta p_{ratio_{12}}$, $\Delta p_{ratio_{23}}$, and $\Delta p_{ratio_{13}}$ defined in (4) are reduced.

Fig. 5 shows the power sharing performance and bus voltage waveform for a generation dominant situation where NDG produces maximum power and loads do not consume power. Fig. 5 also shows that $\Delta p_{ratio_{12}}$, $\Delta p_{ratio_{23}}$, and $\Delta p_{ratio_{13}}$ are reduced. As a result, it can be confirmed that the power sharing accuracy is improved. In the case of the load dominant situation, it can be confirmed that the phenomenon that the bus voltage drops below V_{min} is alleviated. These simulation results confirm the improvement of the voltage regulation performance.

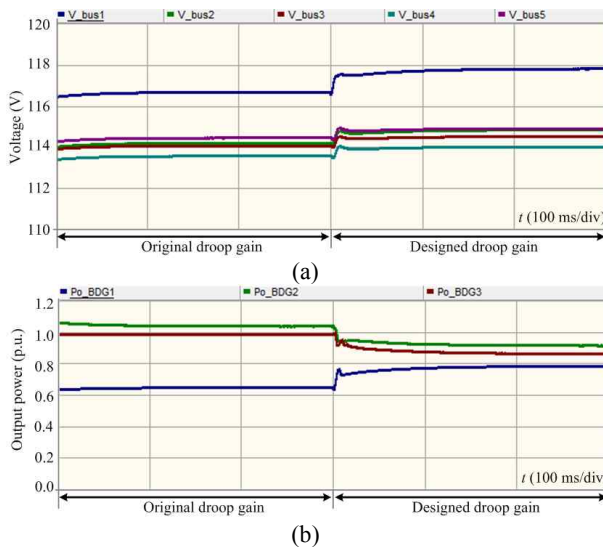


Fig. 4. Simulation results at load dominant situation. (a) Bus voltage. (b) Output power of BDGs.

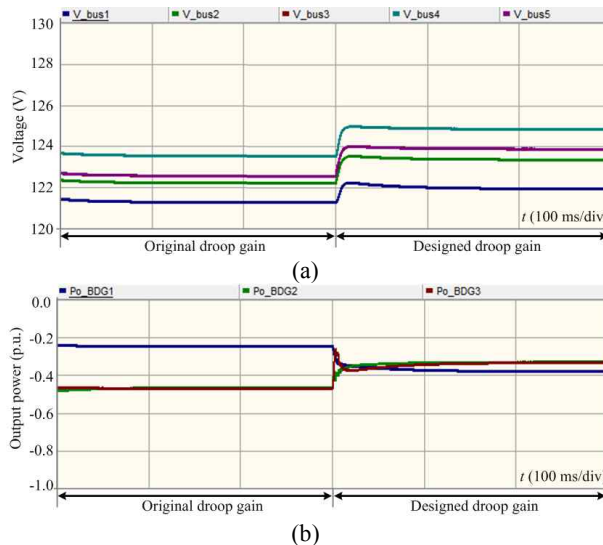


Fig. 5. Simulation results at generation dominant situation. (a) Bus voltage. (b) Output power of BDGs.

CONCLUSION

In this paper, the effect of line resistance on the droop control performance is analyzed. When applying the conventional design method of the droop gain, the power sharing accuracy and the voltage regulation performance are degraded by the line resistance. In order to analyze the complex line configuration, a voltage sensitivity matrix including droop control characteristics was derived. Based on this analysis, the droop control design method was proposed. The simulation results provide the validity of the proposed design method.

TABLE I
PARAMETERS OF DC MICROGRID SYSTEM

Parameters	Symbol	Value
Nominal voltage	V_{nom}	120 V
Voltage variation width	ΔV_{def}	6 V
Rated power of BDG 1	$P_{rated 1}$	1500 W
Rated power of BDG 2	$P_{rated 2}$	750 W
Rated power of BDG 3	$P_{rated 3}$	750 W
Maximum power of load 1	$P_{load 1}$	1000 W
Maximum power of load 2	$P_{load 2}$	700 W
Maximum power of load 3	$P_{load 3}$	700 W
Maximum power of NDG	P_{NDG}	1100 W
Line resistance btw 1st and 2nd bus	R_{12}	0.3 Ω
Line resistance btw 2nd and 3th bus	R_{23}	0.22 Ω
Line resistance btw 2nd and 5th bus	R_{25}	0.22 Ω
Line resistance btw 3th and 4th bus	R_{34}	0.22 Ω
Line resistance btw 4th and 5th bus	R_{45}	0.22 Ω
Line resistance btw 3th and 5th bus	R_{35}	0.3 Ω

TABLE II
DESIGN RESULTS OF DROOP GAIN

# B D G	By (2)	Load dominant			Generation dominant		
	R_d	α^{load}	β^{load}	R_d^{load}	α^{gen}	β^{gen}	R_d^{gen}
#1	0.456	1	0.6	0.274	1	1	0.456
#2	0.912	1.752	0.6	0.958	2.120	1	1.934
#3	0.912	1.752	0.6	0.958	2.120	1	1.934

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