Energies **2014**, *7*, 6477-6491; doi:10.3390/en7106477

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Voltage Control Scheme with Distributed Generation and Grid Connected Converter in a DC Microgrid

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External Editor: Neville Watson

Received: 20 March 2014; in revised form: 19 September 2014 / Accepted: 25 September 2014 / Published: 10 October 2014

Abstract: Direct Current (DC) microgrids are expected to become larger due to the rapid growth of DC energy sources and power loads. As the scale of the system expends, the importance of voltage control will be increased to operate power systems stably. Many studies have been performed on voltage control methods in a DC microgrid, but most of them focused only on a small scale microgrid, such as a building microgrid. Therefore, a new control method is needed for a middle or large scale DC microgrid. This paper analyzes voltage drop problems in a large DC microgrid and proposes a cooperative voltage control scheme with a distributed generator (DG) and a grid connected converter (GCC). For the voltage control with DGs, their location and capacity should be considered for economic operation in the systems. Accordingly, an optimal DG allocation algorithm is proposed to minimize the capacity of a DG for voltage control in DC microgrids. The proposed methods are verified with typical load types by a simulation using MATLAB and PSCAD/EMTDC.

Keywords: voltage control; DC microgrid; distributed generation; optimal allocation; battery energy storage system

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1. Introduction

A majority of microgrids adopt an Alternating Current (AC) system to utilize the existing AC power grid. However, currently, a microgrid includes a large amount of DC output type distributed generations and energy storage, such as photovoltaics (PV), electric vehicles, and super capacitors. With this change, a DC microgrid, as well as a hybrid AC/DC microgrid, is gradually increases in efficiency in connecting the DC output type generation to a microgrid [1–3]. In addition, such points have been the driving force for research on DC distribution systems with a low voltage level distribution system as well as a medium/long distance distribution system.

Past studies of voltage control for DC microgrids have focused on a control method of the AC/DC converter at the point of common coupling and a distributed generation to regulate bus voltages in a DC distribution system. Some of the studies examined a control method of power electronics to control the bus voltages in DC distribution systems. For a bi-directional AC/DC inverter in a DC microgrid, a voltage control method and voltage balance circuits were proposed and examined by computer simulations [4]. However, the proposed voltage control has difficulty in applying to a long distance DC system since the voltage balancer is placed on the AC/DC inverter. In addition, an AC/DC bi-directional inverter is used for DC-bus voltage control in DC distribution systems [5]. Since the bi-directional inverter at the point of common coupling continuously regulates overall system voltages, the inverter can improve the operational reliability and availability in a DC system [6–8]. However, voltage control with only a bi-directional inverter might not cover all the system voltages as a DC distribution system becomes larger. This is because the systems can have a large voltage difference between the point of common coupling and the end bus. Therefore, a local voltage control method is needed for a medium/long distance system.

Many previous studies on a local voltage control method by distributed generation have adopted droop concepts to control the bus voltage in a DC microgrid [9,10]. The author proposed a control method for the grid inverter and battery energy-storage to control DC grid voltage independently using droop control. The author reported that the method brings high reliability, high-flexibility and maintenance-free operation to the system [9]. However, the control method has difficulty in being applied to a large DC microgrid because the DC distributed system in the paper is a one bus system. A voltage control method in a DC power system that combines fuzzy control and droop was presented to manage energy storage. The methods based on the droop concepts introduced in these studies provide stable voltage control. Voltage control with DC/DC converters for energy storage focused on energy balance with energy storage [10].

The aforementioned studies focused only on one bus, short distances, and low voltage levels. With the need for a medium/long distance DC grid, an adaptable voltage control method for any distance is needed. A more flexible voltage control method will be vital for reinforcement of the future DC microgrid as well as an existing DC system. Furthermore, an optimal DG placement algorithm is proposed because the proposed voltage control is performed with power control in the DC microgrid.

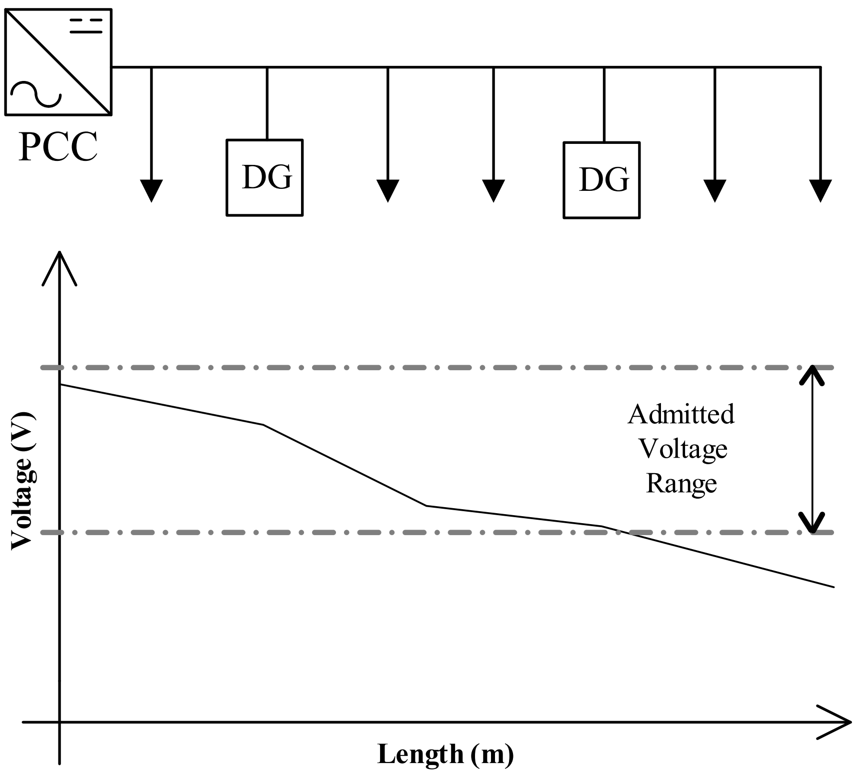
This paper is organized as follows. Section 2 examines the voltage drop problem and explains the concept of cooperative voltage control with a grid connected converter (GCC) and distributed generation (DG). In Section 3, an optimal DG allocation is proposed for economical control because the location of the DG is an important issue for voltage control in a DC microgrid. In Section 4, the proposed voltage control method is described in detail with a simple example. Finally, the proposed methodologies are verified by PSCAD/EMTDC and MATLAB.

2. Cooperative Voltage Control Scheme in a DC Microgrid

2.1. Voltage Drop Problem in a Radial DC Microgrid System

In a typical DC microgrid with a radial topology, power flows from its point of common coupling (PCC) to the end bus in one direction. Therefore, a voltage drop problem can occur with a line voltage drop and the lowest bus voltage is formed at the receiving end in the system. The value of the line voltage drop increases in proportion to the load current magnitude and the line length in the microgrid. Figure 1 shows a typical voltage profile in a DC microgrid. In this instance, some bus voltages, normally at the end of a system, are out of the admitted voltage range as the distribution line becomes longer. Moreover, certain sensitive loads without a voltage compensator could malfunction and the voltage stability might deteriorate further as the bus voltages become seriously diminished. Therefore, a voltage control method is needed to maintain the system bus voltage within an appropriate range.

Figure 1. Voltage profile in a DC microgrid.



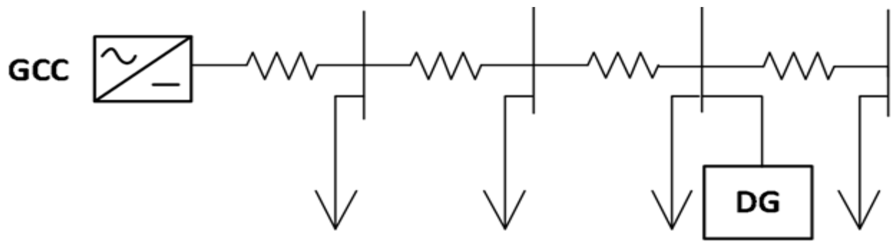
In recent studies regarding system voltage control in a DC microgrid, the main focus was on how to control a DG and energy storage device to maintain only one bus voltage within the required range. However, the controlled target bus voltage should be extended to all bus voltages as the system is expanded. This requires a new control scheme different from the previous method used in a small scale DC microgrid, and the new control scheme should guarantee that voltages at all buses are maintained within the appropriate voltage range.

2.2. Cooperative Voltage Control Scheme with a Grid Connected Converter and a Distributed Generation

In an AC power system, a variety of devices, such as shunt capacitors, shunt reactors, transformers, static VAR compensators (SVC), STATCOMs, are used to control system voltages because the voltages are influenced considerably by reactive power. However, there is no reactive power in a DC system, and system voltages are determined by active power-flow. Therefore, a different scheme from an AC system is needed to regulate system voltages in a DC system.

In this paper, a grid-connected converter and a controllable distributed generator, which includes an energy storage device, are used for the cooperative voltage control in a DC microgrid as shown in Figure 2. Advantages of each device could be emphasized through the cooperative voltage control because the devices have opposite characteristics.

Figure 2. The proposed voltage control topology in a radial DC microgrid.



A Grid-Connected Converter (GCC) acts as an on-load tap-changing transformer in an AC power system from a voltage control point of view, and it can efficiently control all system voltages at the secondary side of the converter by a PWM switching operation. The converter is located at the PCC in the proposed control scheme to control the voltages at all buses in a DC microgrid. Therefore, the GCC is used for voltage control at the PCC only, and an additional series converter is not considered in this paper. Furthermore, the line voltage drop increases with load current, especially at a low bus voltage, which causes a large voltage difference between some buses in a radial DC microgrid. In the case where a large voltage difference exists between some buses and only the GCC controls the system voltages, maintaining all system voltages in the admitted range can be a problem. This problem cannot be solved with the GCC only, because voltage control of the GCC is performed either by increasing or decreasing system voltages.

A DG is a good solution for the problem mentioned previously. A DG can control system voltages locally in a radial DC microgrid because all the buses in the system have quite different voltage sensitivities with respect to the injected power from the DG. In particular, a controllable DG with the capability of charging or discharging, such as an energy storage device, can solve the over voltage problem and under voltage problem as well. However, the overall over voltage or under voltage problems in the entire system cannot be solved if only a DG is used for voltage control. In addition, the generation costs of the DG should be an essential concern for economical control operations because the voltage control with the DG is performed by power in a DC microgrid.

Voltage control in all power systems, including a DC microgrid, is closely related to voltage sensitivities. Similar to an AC system, a bus with high voltage sensitivity usually has low voltage and a bus with low voltage sensitivity has high voltage in a DC microgrid. Because a relatively large amount of power is required to control the voltage at a bus with low voltage sensitivity, a GCC should control the voltage at a bus with the lowest voltage sensitivity. Furthermore, voltage sensitivities in a DC microgrid should be considered to maintain system voltages, especially with voltage control with a DG. This is because a small amount of power is needed for voltage control and a DG usually has limits of current and generation capacity. Therefore, the voltage at a bus with high voltage sensitivity should be controlled by a DG.

Based on the aforementioned fact, a cooperative voltage control method is proposed as follows:

- A GCC controls the voltage of a bus with the lowest voltage sensitivity in a DC microgrid. A bus with a higher voltage normally has lower voltage sensitivity. Therefore, a large generating power is needed if a bus voltage is controlled by a DG. Therefore, a GCC is suitable for this bus from an economic perspective.
- A DG regulates the lowest bus voltage in a DC microgrid so that the voltage can be controlled with the minimum capacity of the DG. A bus with lower voltage has higher voltage sensitivity, and the voltage can be regulated effectively with a small generated power delivered from a DG.
- A GCC should control its target bus voltage as high as possible to reduce line loss. In addition, this leads to a decrease in the power delivered from a DG because the amount of line voltage drop decreases with high voltage.

Consequently, both overall over voltage and under voltage problems are controlled by a GCC, and a local voltage problem can be solved by a DG. Furthermore, the proposed scheme can reduce the operation cost for voltage control from a long term perspective because the power delivered from a DG can be reduced and the overall voltage can be regulated.

3. Optimal DG Allocation Algorithm

Voltage control by a DG has a large dependency on its location in a power system. Moreover, voltage control in a DC microgrid necessitates power generation from a DG. Therefore, the more controlled the bus voltage is, the larger the amount of power needed from a DG. This involves increasing the capacity and thus, the installation cost of the DG. Therefore, an optimal DG allocation is essential for economical voltage control with minimum capacity and power generation from a DG.

In the proposed algorithm, a battery energy storage system is considered as a DG. Generation cost of the battery is assumed to be always constant regardless of the system status, which is based on a fixed electricity price. If the loss with charging and discharging is small enough to be neglected, and the net charging and discharging energy is zero, it can be assumed that the generating cost is small enough and can be ignored. Based on these assumptions, an algorithm is proposed such that the battery energy capacity and therefore, the installation cost, are minimized. This leads to a minimization of the operation cost because the installation cost is dominant and the generation cost is assumed to be negligible.

Voltage control by a DG has a heavy reliance on the controlled bus voltage and voltage sensitivity. As mentioned previously, a DG should regulate the lowest bus voltage in a DC microgrid for economical operation. In an AC power system, the voltage sensitivity is generally evaluated using V-Q sensitivity analysis with a Jacobian matrix. The elements of the Jacobian matrix give the sensitivity between power-flow and bus voltage changes [11]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{1}$$

where,

ΔP = incremental change in bus active power injection;
ΔQ = incremental change in bus reactive power injection;
Δθ = incremental change in bus voltage angle;
ΔV = incremental change in bus voltage magnitude.

At each operating point, we may keep active power constant and evaluate voltage stability by considering the incremental relationship between reactive power and system voltage. Hence, the voltage sensitivity is derived as Equation (2) [8].

$$\Delta \boldsymbol{V} = [\boldsymbol{J}_R]^{-1} \Delta \boldsymbol{Q} \tag{2}$$

where,

$$\boldsymbol{J}_R = [\boldsymbol{J}_{QV} - \boldsymbol{J}_{Q\theta} \boldsymbol{J}_{P\theta}^{-1} \boldsymbol{J}_{PV}] \tag{3}$$

The voltage sensitivity in a DC system can be given by a Jacobian matrix, similar to an AC system, as expressed in Equation (4).

$$\Delta \boldsymbol{V} = [\boldsymbol{J}]^{-1} \Delta \boldsymbol{P} \tag{4}$$

In a DC power system, the mathematical expression of voltage sensitivity is much simpler than that of an AC power system because phase angle and reactive power is absent. However, a numerical analysis method is needed to analyze the expression and it is difficult to find a relationship between the power and voltage deviation because the inverse of the Jacobian matrix is included in the voltage sensitivity expression. Therefore, an approximate expression for voltage sensitivity is derived by a small-signal analysis method in this paper to investigate the relationship between power and voltage deviation with respect to the system operating point.

The following voltage equation is defined to express a change of voltage sensitivity caused by injected power at other buses:

$$V_i - V_1 = \sum_{k=1}^{n} R_{ik} \frac{P_k}{V_k} \tag{5}$$

It is assumed that the value of V_1 is known and kept constant because bus 1 is located at the point of common coupling and is controlled by a grid connected converter. The voltage difference between the 1st bus and the *i-th* bus is on the right hand side. Based on Equation (5), Equation (6) expresses a change of voltage at the *i-th* bus when an injected power at the *j-th* bus changes:

$$(V_i + \Delta V_i) - V_1 = \left(\sum_{\substack{k=1 \\ k \neq j}}^{n} R_{ik} \frac{P_k}{V_k + \Delta V_k} \right) + R_{ij} \frac{P_j + \Delta P_j}{V_j + \Delta V_j} \tag{6}$$

where, the subscript *i*, *j* and *k* indicate the indices of buses in a microgrid: The bus where we evaluate voltage sensitivity, the bus where power is injected, and the remaining buses, respectively.

The term ΔP_k can be neglected because injected power at the other bus is kept constant. In addition, the term ΔV_1 can be neglected because V_1 is constantly regulated by a grid connected converter at the point of common coupling. With injected power at the *j-th* bus, the approximated voltage sensitivity expression of the *i-th* bus is derived in Equation (7).

$$\frac{\Delta V_i}{\Delta P_j} \cong \frac{V_i^2}{(V_i^2 + R_{ii}P_i)V_j}\left(R_{ij} - \sum_{\substack{k=1 \\ k\neq i}}^{n} \frac{R_{ik}R_{kj}P_k}{V_k^2 + R_{kk}P_k}\right) \tag{7}$$

The proposed optimal DG allocation algorithm is presented as follows, and a partial derivative of the voltage with respect to the bus active power is the voltage sensitivity, which is calculated from Equation (4). Table 1 lists the abbreviations used in the proposed algorithm.

Table 1. Definition of the abbreviation in an optimal DG allocation algorithm.

Abbreviation	Definition
Bus *H*	Bus with the highest voltage in the DC microgrid
Bus *L*	Bus with the lowest voltage in the DC microgrid
Bus *I*	Bus with the highest voltage sensitivity affected by injected power into Bus L
V_{High}	Voltage at bus H
V_{Low}	Voltage at bus L
V_{Max}	Maximum voltage limit in the DC microgrid
V_{Min}	Minimum voltage limit in the DC microgrid
N_{GCC}	Ratio of voltage at the secondary side of GCC on rated voltage of the system

Step 1.

- Solve the power-flow calculation for the DC system and choose Bus *H* and Bus *L*.
- Check the voltage violation condition to identify need of a battery as follows:

$$|V_{High} - V_{Low}| > V_{Max} - V_{Min} \tag{8}$$

- Check Bus I, and add Bus I to the list as a candidate for optimal DG allocation.
- A battery is not required if Equation (8) is not satisfied.

Step 2.

- Change N_{GCC} step size until the voltage at Bus *H* exceeds V_{Max}.
- Check the voltage violation condition to identify need of a battery as follows.
- A battery is not required if Equation (8) is not satisfied.
- Check Bus *I* and add to the list if Bus *I* is changed.

Step 3.

- Change the power at Bus *I* as Equation (9), and repeat this procedure until P_I becomes smaller than the tolerance value.

$$\Delta P_I = \frac{(V_{Max} - V_{Min}) - (V_{High} - V_{Low})}{\frac{\partial V_{High}}{\partial P_I} - \frac{\partial V_{Low}}{\partial P_I}} \tag{9}$$

- If Equation (8) is satisfied, check Bus *I* and add to the list if Bus *I* is changed.

Step 4.

- Repeat steps 2 and 3 until the voltages at all buses are within the admitted range.
- In this step, the minimum capacity of the battery is determined when the battery is located at Bus *I*.

Step 5.

- Repeat steps 1 to 4 if new buses are added to the list of bus *I* through steps 1 to 4.
- Compare the required capacity of the battery according to the location of the battery. The bus where the required capacity of the battery is the smallest is the optimal location.

4. Cooperative Voltage Control Method

As mentioned above, a GCC and a DG are used for the proposed voltage control method. The GCC controls a bus voltage at the PCC, which has the highest voltage and the lowest voltage sensitivity. The DG controls a lower bus voltage with the highest sensitivity. To implement this scheme, the voltage profile at all buses should be obtained using a supervisory controller in an energy management system (EMS).

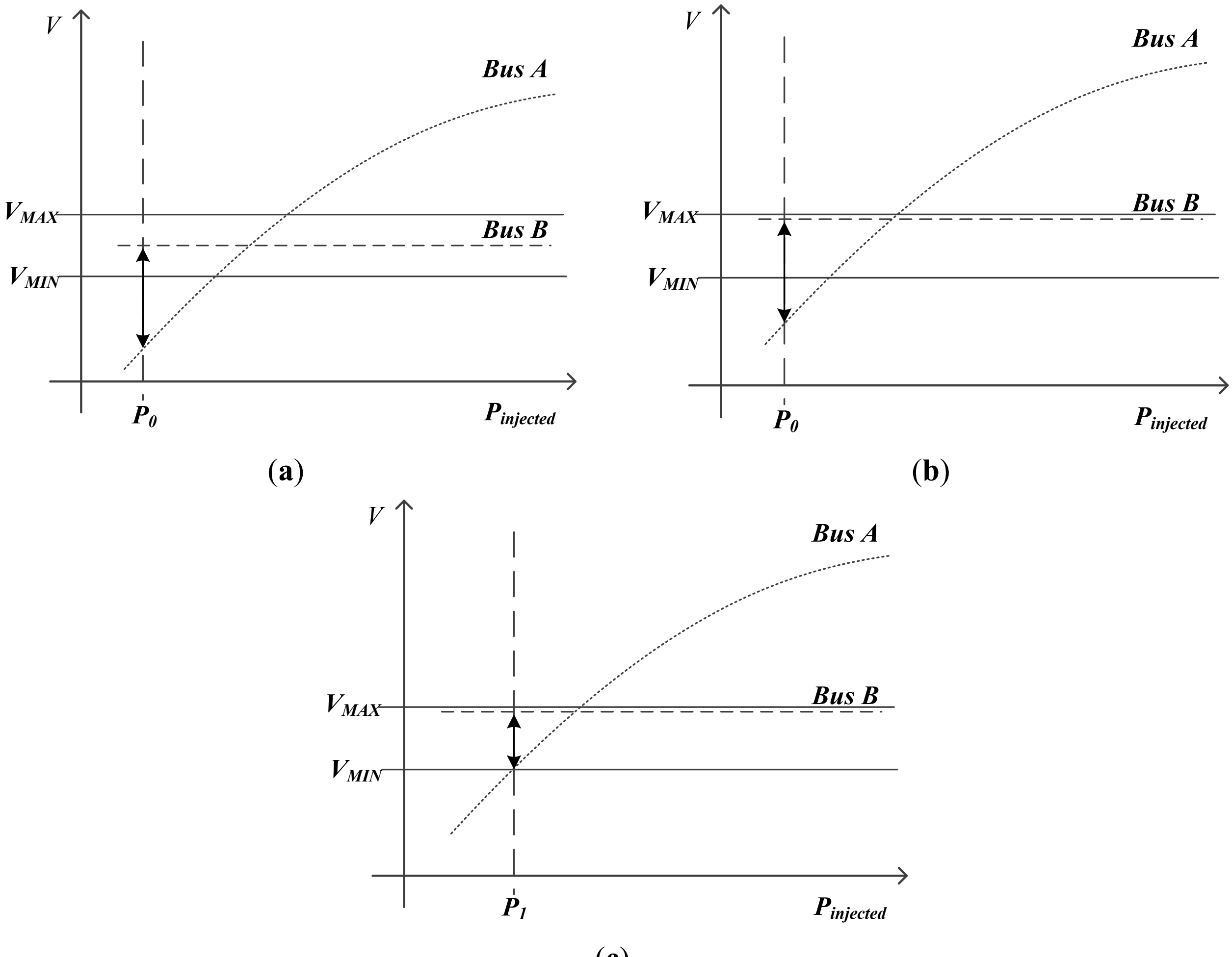
The supervisory controller also provides the reference signal to both voltage control devices, such as the GCC and the DG. In addition, it is assumed that the location of the DG can be determined by the proposed optimal DG allocation algorithm in this paper. A simple example with the test system is presented to explain how voltage control is implemented and the effects of the proposed control. Figure 3 gives an example of the voltage profile when the proposed cooperative voltage control method is adopted.

At an initial state in Figure 3a, the voltage at bus *B* is fixed at 1.0 pu because it is controlled by the GCC. However, the voltage at bus *A* is out of the admitted range and the voltage difference between bus *A* and *B* is larger than that between V_{Max} and V_{Min}. If the voltage difference between bus *A* and *B* is small enough, a DG will not participate in the proposed voltage control for economical operation.

In Figure 3b, the voltage at the secondary side of the GCC increases until the voltage at bus *B*, which has the highest voltage in the system, reaches the maximum voltage limit with a margin (1.04 pu in this paper). Consequently, none of the bus voltages exceeds the maximum voltage limit, but the voltage at bus *A* is still not within the required range.

Because the GCC cannot increase the voltage further (if the GCC tries to raise the system voltages, the voltage at bus *B* exceeds V_{Max}), to increase the voltage at bus *A*, the output power from the connected DG should be increased locally until the voltage difference between bus *A* and *B* equals the voltage difference between V_{Max} and V_{Min}. As a result, the voltage difference between the two buses is reduced to be the same as the one with V_{Max} and V_{Min} even though the voltage at bus *B* is unaffected by the power from the DG because of the voltage control of the GCC. Finally, all the bus voltages in the system can be regulated with the minimum power delivered from the DG as shown in Figure 3c.

Figure 3. (**a**) Initial voltage profile; (**b**) Output voltage of the grid connected converter (GCC) is increased; (**c**) Output power of the DG is increased from P_0 to P_1.



5. Case Studies

5.1. Verification of the Optimal DG Allocation Algorithm

The proposed allocation algorithm is verified in the test system as shown in Figure 4. Although some of the system parameters are not practical for a real system, the proposed algorithm with the test system shows the concept. In the test system, the negative load power means that there is a distributed generator connected to the bus.

Figure 4. A test radial system for the optimal allocation algorithm in MATLAB.

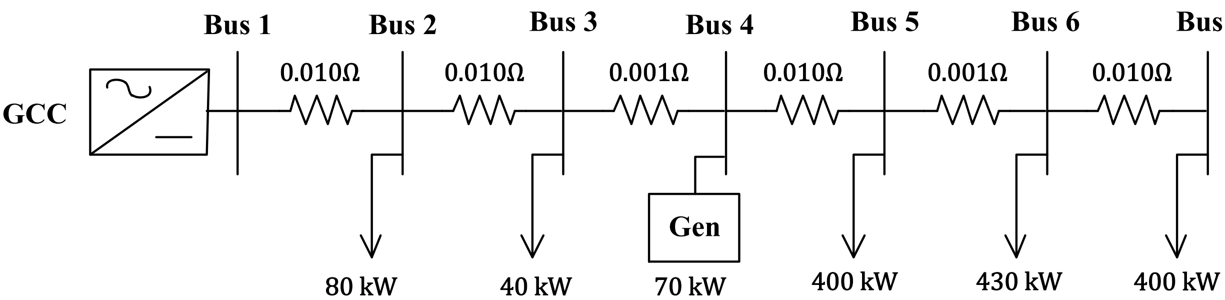


Table 2 lists the line parameters for the test system. Tables 3 and 4 list the results of the proposed optimal DG allocation algorithm. In the results, Buses 5 and, 6 are determined to be candidates for Bus *I*, the optimal location of the DG, because of the high voltage sensitivity with high load power consumption. Among these buses, Bus 6 can be chosen for the optimal location because the required the capacity of the DG is smaller than that at Bus 5 for voltage control. Therefore, the required capacity of the DG for voltage control can be minimized with the proposed algorithm, whereas the overall voltages are maintained within the admitted range.

Table 2. Line parameters for the test system.

Bus Number	Bus Number	Line Resistance (Ω)
1	2	0.010
2	3	0.010
3	4	0.001
4	5	0.010
5	6	0.001
6	7	0.010

Table 3. Results of the algorithm when the DG is located at Bus 5.

Bus Number	Generation Power (kW)	Load Power (kW)	Bus Voltage (pu)
1	7867	-	1.122
2	-	80	1.050
3	-	40	0.986
4	-	−70 (Gen)	0.983
5	1445	400	0.951
6	-	430	0.950
7	-	400	0.992

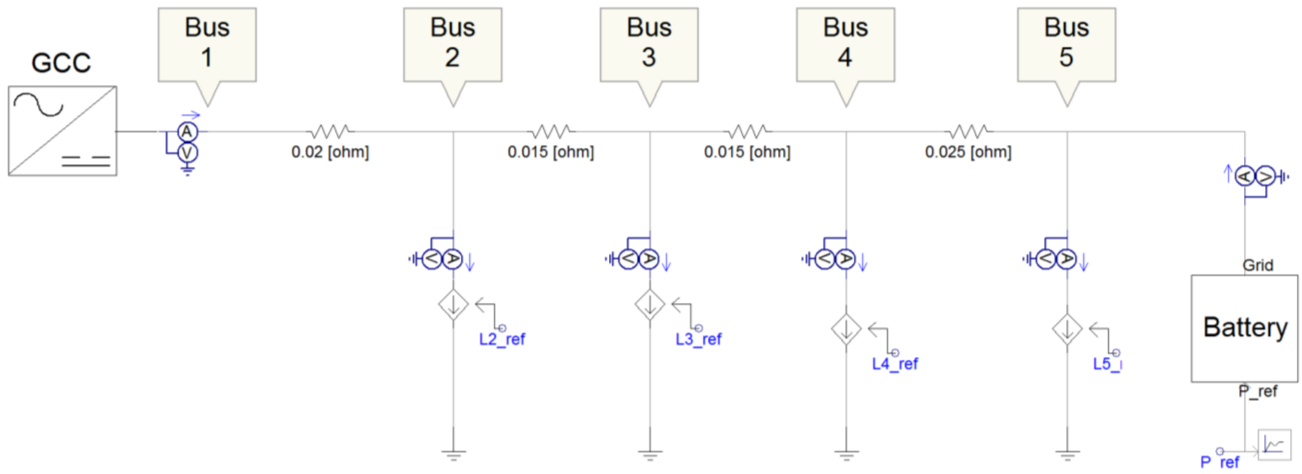
Table 4. Results of the algorithm when the DG is located at Bus 6.

Bus Number	Generation Power (kW)	Load Power (kW)	Bus Voltage (pu)
1	7867	-	1.123
2	-	80	1.050
3	-	40	0.985
4	-	−70 (Gen)	0.983
5	-	400	0.950
6	1425	430	0.951
7	-	400	0.993

5.2. Verification of the Cooperative Voltage Control Method

To verify the proposed cooperative voltage control method, voltage control is implemented in the test radial system as shown in Figure 5 using PSCAD/EMTDC. The test system is connected to an AC grid through the GCC, and includes four load buses and a battery unit as the DG. The location of the battery is determined to be Bus 5 by the proposed optimal DG allocation algorithm in this paper, even though it is obvious that the voltage level of the end bus is the lowest in a radial system.

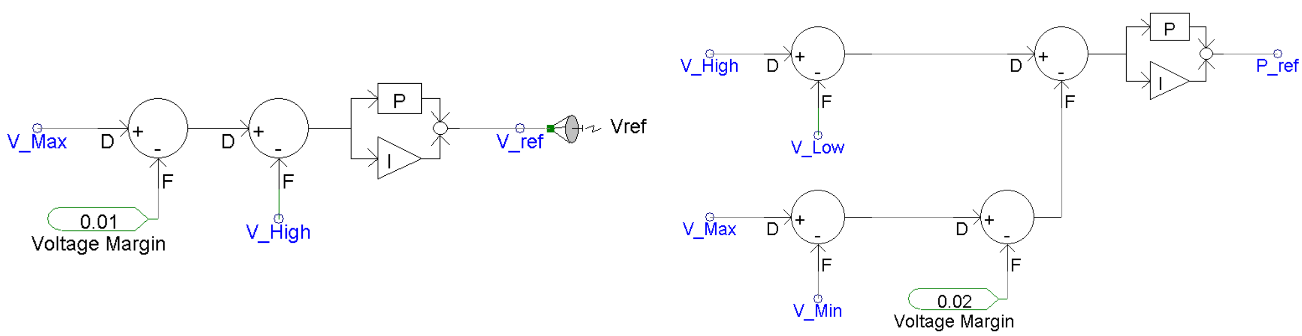
Figure 5. Test radial system for the proposed cooperative voltage control in PSCAD/EMTDC.



The rating voltage is 311 V, which is the peak value of low voltage in an AC distribution system in South Korea. With this voltage rating, the existing load can be connected to a DC distribution system without a rectifier, and the loss from the conversion process can be diminished. In addition, it has the advantage of high feasibility because of the easier connection of the load in a DC distribution system implementation [9].

The controllers are designed based on the proposed cooperative voltage control method. Firstly, a controller for the GCC is presented in Figure 6a. The measured bus voltage and the maximum voltage limit are used to control the voltage at the secondary side of the GCC. This maintains the highest bus voltage in the system at the maximum voltage limit with the voltage margin, which is 0.01 pu in this paper. The voltage reference signal is transferred to PWM to generate a proper voltage. In addition, a controller for the DG is shown in Figure 6b. The output reference signal for the DG is calculated in order for the voltage difference between the highest bus voltage and the lowest bus voltage in the system to be equalized as the voltage gap between the maximum voltage limit and minimum voltage limit. Both controllers are activated when a voltage violation occurs in the system.

Figure 6. (**a**) GCC voltage reference signal controller; (**b**) Battery (DG) reference signal controller.



The loads are the constant power load and are represented by external current source models. The admitted voltage ranges from 0.95 to 1.05 pu. Although the maximum and minimum voltage limit is 1.05 and 0.95 pu, respectively, the bus voltage is regulated to within 0.96 to 1.04 pu considering the voltage margin.

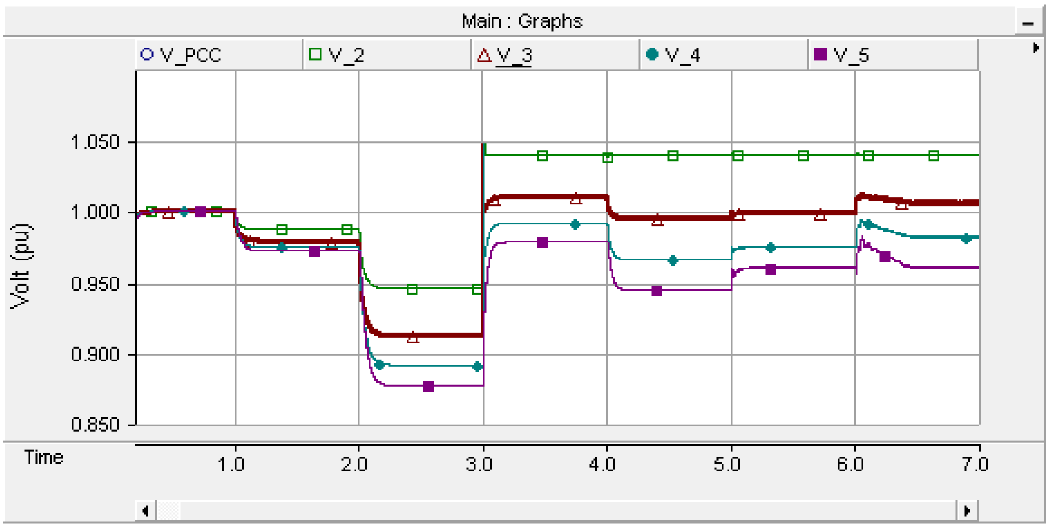
The effect of the cooperative voltage control method is verified when the load power, voltage control and charging modes are changed by following the scenario shown in Table 5. Figure 7 presents the results according to the scenario. In addition, Table 6 lists the detailed bus voltage value and whether or not a voltage violation occurs at each time. The control actions and effects at each time interval are presented as follows.

Table 5. Simulation scenario for the cooperative voltage control method.

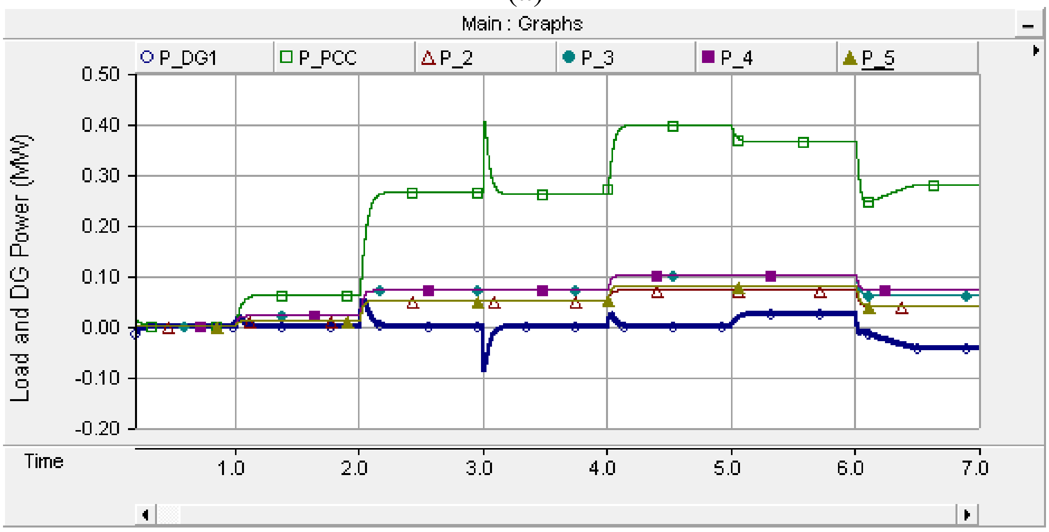
Time	Load Power (kW)				Voltage Control	
	Bus 2	Bus 3	Bus 4	Bus 5	GCC	Battery
0 s	-------------- Initializing --------------					
1 s	10	20	20	10	X	X
2 s	50	70	70	50	O	X
3 s	50	70	70	50	O	X
4 s	70	100	100	80	O	X
5 s	70	100	100	80	O	O
6 s	40	60	70	40	O	O

- 0–1 s: The test system is initialized. No load is connected to the grid.
- 1–2 s: The GCC and the battery do not participate in the proposed voltage control. The voltage at the secondary side of the GCC is fixed to 1.0 pu by the GCC and the power delivered from the battery is zero. The bus voltages are in the required voltage range because the overall load consumption power is low.
- 2–3 s: The overall load increases, and a voltage violation occurs because the voltages of buses 3 and 4 deviate from the required range.
- 3–4 s: The GCC regulates the bus voltage, which is the highest in the DC microgrid. In this case, the voltage at Bus 2 is regulated at 1.04 pu by the GCC, and all bus voltages remain in the admitted range.
- 4–5 s: The load consumption powers are increased further, and the voltage at Bus 5 falls to 0.944 pu. Although the bus voltages are controlled by the GCC, some bus voltages are out of the admitted range.
- 5–6 s: The GCC participates continuously in the proposed voltage control and the battery starts controlling the local voltage. Power is delivered from the battery at Bus 5 to boost the voltage that is under the minimum voltage limit. As a result, all bus voltages are within the normal range.
- 6–7 s: The GCC and battery still participates in the proposed cooperative voltage control. The power consumption of some loads is decreased. Therefore, the power delivered from the battery might not be essential to regulate the bus voltages. This makes the battery change modes from discharging to charging. However, if an uncontrolled generator, such as a renewable energy source, produces a large amount of output, the role of the battery is vital in controlling the voltage. In this case, the bus voltages could be regulated, even though the battery is charged. Therefore, in this case, the charging power is consumed by a battery to recover the state of charge (SOC) of the battery.

Figure 7. (**a**) Result of simulation scenario: Bus Voltage; (**b**) Result of simulation scenario: Injected power from the DG at Bus 5.



(**a**)



(**b**)

Table 6. Simulation results of Bus voltage and voltage violation.

Time	Bus Voltage (pu)				Voltage Control		Voltage Violations
	Bus 2	Bus 3	Bus 4	Bus 5	GCC	DG	
0 s	--------------- Initializing ---------------						
1 s	1.0	0.979	0.974	0.971	X	X	X
2 s	0.945	0.912	0.891	0.876	X	X	**O**
3 s	1.04	1.01	0.991	0.978	O	X	X
4 s	1.04	0.995	0.966	0.944	O	X	**O**
5 s	1.04	0.999	0.975	0.960	O	O	X
6 s	1.04	1.006	0.982	0.959	O	O	X

6. Conclusions

Due to the increasing number of distributed generations that generate a DC output, the scale of the DC grid is being expanded gradually in power systems. Since previous studies of DC microgrid voltage control are limited to systems with only one bus for short distances, a novel cooperative voltage control method with a grid connected converter and a distributed generator is proposed to apply flexibility for a long distance DC microgrid. The proposed method guarantees that all bus voltages in a radial DC microgrid are regulated in the desired range and reduces the delivered power from a DG used for voltage control. Furthermore, the future research of voltage control will be extended to a DC microgrid with multiple DGs and a mesh structured power system.

Since power from DG is needed for voltage control in a DC microgrid, economic issues should be considered when DG is used for voltage control. In addition, the required amount of power of DGs for voltage control is closely related to their location. With these considerations, an optimal DG allocation algorithm for voltage control is proposed to minimize the required capacity of DGs (battery storage in this paper), voltage regulation cost, and operation cost. In this paper, it is assumed that the generation cost of the battery is always constant, regardless of the system status based on a fixed electricity price. However, the generation cost of the battery is not always constant because the electricity price is not fixed in a real system. Consequently, the optimal DG allocation algorithm should include this consideration for a more accurate economic evaluation.

The proposed methods are verified by MATLAB and PSCAD/EMTDC. A 7-bus system is adopted for the optimal DG allocation algorithm. The case study of a 5 bus DC microgrid shows how the proposed method performs and how voltage control devices (GCC and DG) regulate the overall system voltage.

Acknowledgments

This work was supported by the INHA UNIVERSITY Research Grant.

Author Contributions

Jong-Chan Choi carried out the main research tasks and wrote the full manuscript, and Ho-Yong Jeong proposed the original idea, analyzed and verified the results and the whole manuscript. Jin-Young Choi provided technical support to verify the proposed algorithm in simulation software. Dong-Jun Won, Sun-Ju Ahn, and Seung-il Moon validated and double-checked the proposed algorithm, the results, and the whole manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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