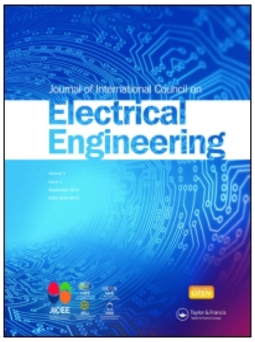

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ABSTRACT
Microgrids are small-scale power grids that combine a renewable energy source with an energy storage system (ESS) to power loads. They are operated in connection with commercial power grids and operate independently in mountainous areas where commercial power grids are not provided. Microgrids are mainly classified into AC and DC types. Independently operating micro-grids typically use diesel generators to supply power to customers. However, the use of distributed generators, such as solar power, wind turbines, and ESSs, is increasing worldwide as conventional fossil-fueled power systems face the problem of gradual depletion of resources. DC microgrids are being actively studied because they require only voltage control, and most distributed generators produce DC power. In particular, the voltage of the DC bus must be maintained using ESSs to maintain the voltage of the microgrids. In this study, we propose two stable power supplies, namely, MAIN ESS for voltage control in DC microgrids and SUB ESS for power supply of loads, and a stable operation by switching a voltage-controlled ESS unit at the MAIN ESS dropout. We demonstrate that DC microgrids can be modeled and operated stably throughout PSCAD/EMTDC.

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KEYWORDS
DC microgrid; load sharing; ESS voltage regulation; power control; centralized control

1. Introduction

Research on DC microgrids in mountainous areas has been actively conducted due to the increase in new renewable energy sources (RESs) and the technological development of energy storage systems (ESSs). Microgrids are local grids with a number of RESs, ESSs, and local loads, which can be considered independent systems that can operate in either grid-connected or islanded mode [1,2]. They can be divided into AC and DC microgrids depending on the link type. AC microgrids have the advantage of using conventional grids as they are, but are prone to synchronization, stability, and reactive power problems. DC microgrids do not encounter the same problems, but a disadvantage is that the specification of the operating voltage is not set, and protection is difficult. An advantage is that the power generated by each power source is two times less than the power conversion of DC–DC–AC or AC–DC–AC; therefore, the installation cost and system loss are small, and only the voltage of the DC bus is managed [3]. Research on DC microgrids has recently attracted considerable interest because DC power sources are needed for the fast-paced operations of information communication equipment and data centers [4–7]. Nevertheless, RESs with intermittent output characteristics in independent microgrids can cause power imbalance problems. A countermeasure against the voltage control unit is also necessary in case of failure or inspection of the ESS that maintains the DC bus voltage. In this study, we propose an algorithm for stable operation of DC microgrids and an output adjustment value of ESS according to each case. We model a DC microgrid using the proposed algorithm by PSCAD/EMTDC and classify it into two cases, namely, MAIN ESS connect and outage. The algorithm and voltage control method are verified by showing the balancing of power and keeping the DC voltage constant.

2. Modeling using PSCAD/EMTDC

In this study, we model and simulate a DC microgrid and propose an operation algorithm using PSCAD/EMTDC software.

2.1. DC microgrid

DC microgrid modeling consists of diesel generator, DC load, photovoltaic (PV) generation system, and MAIN/SUB ESS. Figure 1 and Table 1 show the configuration of the DC microgrid and the specification of each component.

2.1.1 Photovoltaic

The model is represented using the perturb-and-observe method, one of the maximum power point

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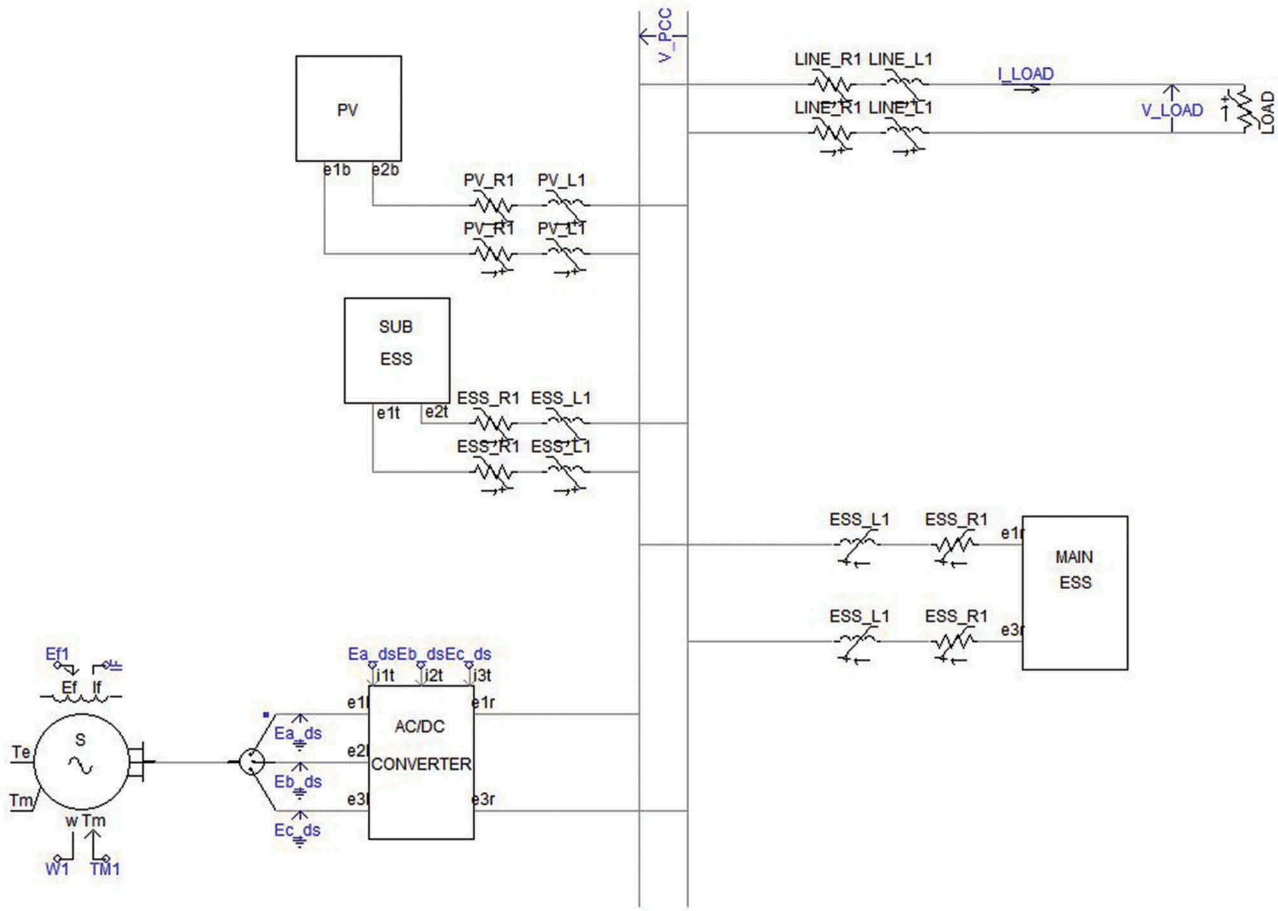

Figure 1. Configuration of DC microgrid.

Table 1. Specification of each component of DCmicrogrid.

	Rated Power	Distance from DC-bus
PV	100kW	500m
MAIN ESS	100kW	500m
SUB ESS	50kW	1000m
DIESEL GENERATOR	100kW	100m

tracking (MPPT) methods, to maximize the power output from the PV module, as shown in Figure 2 [8].

A risk of voltage problems exist due to the power imbalance in the microgrid if the generation power of the PV system is larger than the power consumption and the state of charge (SOC) of all ESSs is 80% or more. Thus, the generation amount of the PV system has to be controlled when the predetermined condition is satisfied [9]. In the present study, we limit the power generation of PV by using the variable limiter of the current reference of the PV system. The limiter is normally limited to 1.5 times the rated power of the existing limiter. However, if the power generation of the PV power generation system should be limited, the power generation amount is limited to 70% of the rated current of the PV. The controller structure is shown in Figure 3.

2.1.2 Diesel generator

The diesel generator is composed of a synchronizer. The controller consists of an exciter for adjusting the output voltage and a governor for adjusting the active power output. The controllers of the exciter and governor used in this study are shown in Figures 4 and 5 [10].

2.1.3 AC/DC converter

An AC/DC converter that converts the AC voltage supplied from the diesel generator to a DC voltage of 750 V is required. Therefore, the two-level pulse-width modulation AC/DC converter is modeled as a power conversion device, as shown in Figure 6. In this study, we control the rated output to maximize the efficiency of the diesel generator, thereby minimizing the problems related to depletion, energy efficiency, and environmental pollution caused by fossil fuels. However, depending on the situation of the DC microgrid, the output reference value of the converter operates by selecting between the rated output and the output reference value according to the operating mode.

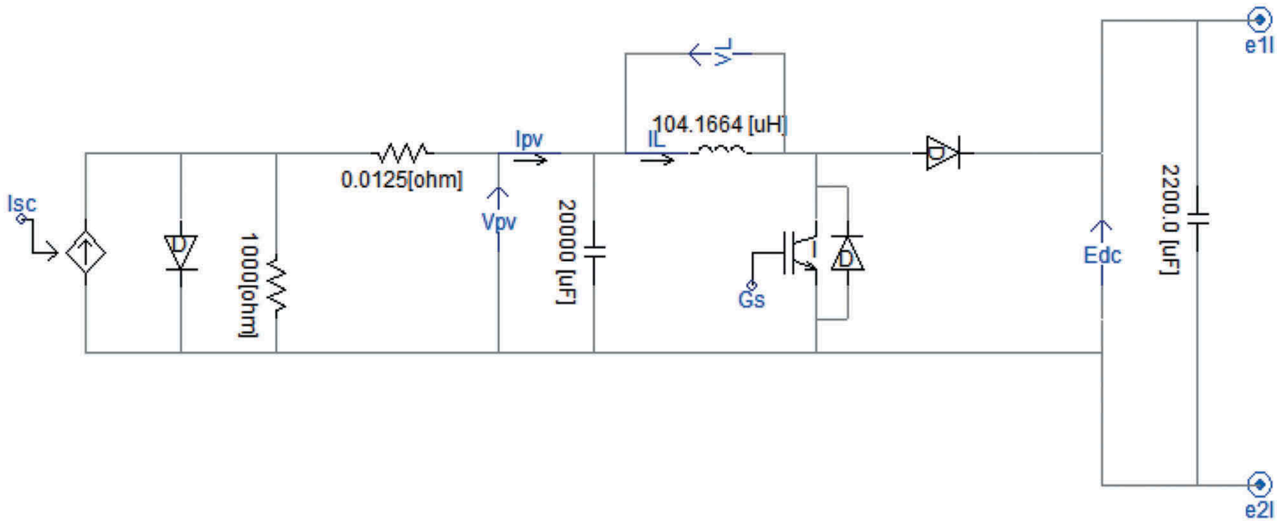

Figure 2. Photovoltaic model.

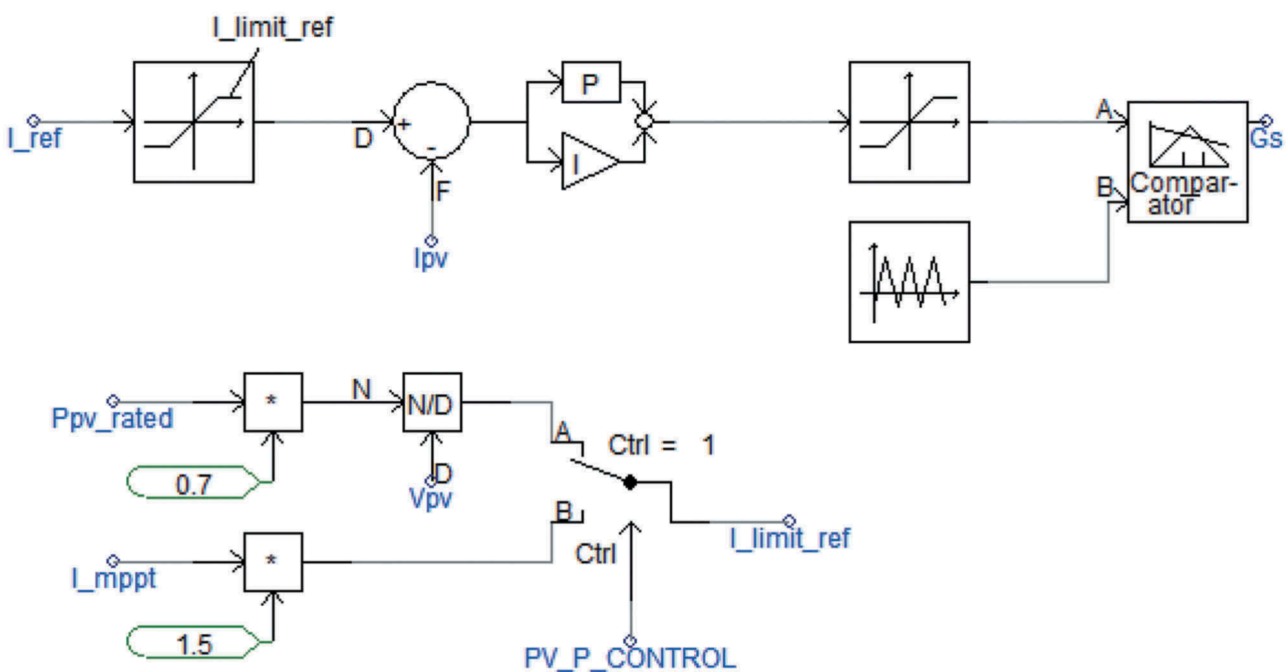

Figure 3. Power Control of Photovoltaic model.

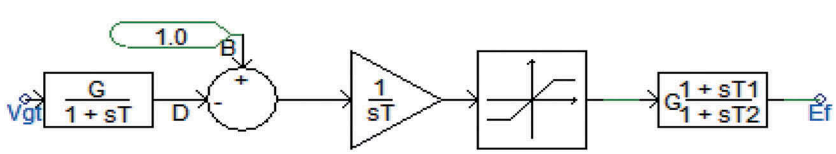

Figure 4. Exciter of Diesel generator model.

2.1.4 Ess

ESS modeling is composed of a capacitor, voltage source, and insulated-gate bipolar transistor (IGBT), as shown in Figure 7. The ESS has a structure of an interleaved DC–DC buck-boost converter, which operates in charge and discharge modes by switching six IGBT devices. In the charge mode, the upper-side IGBT switches of S1,S3, and S5 are switched and

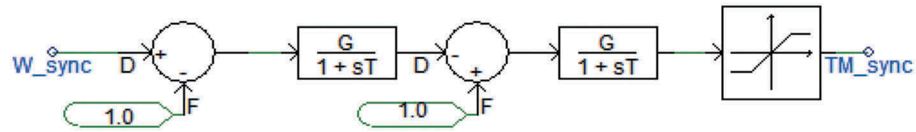

Figure 5. Governor of Diesel generator model.

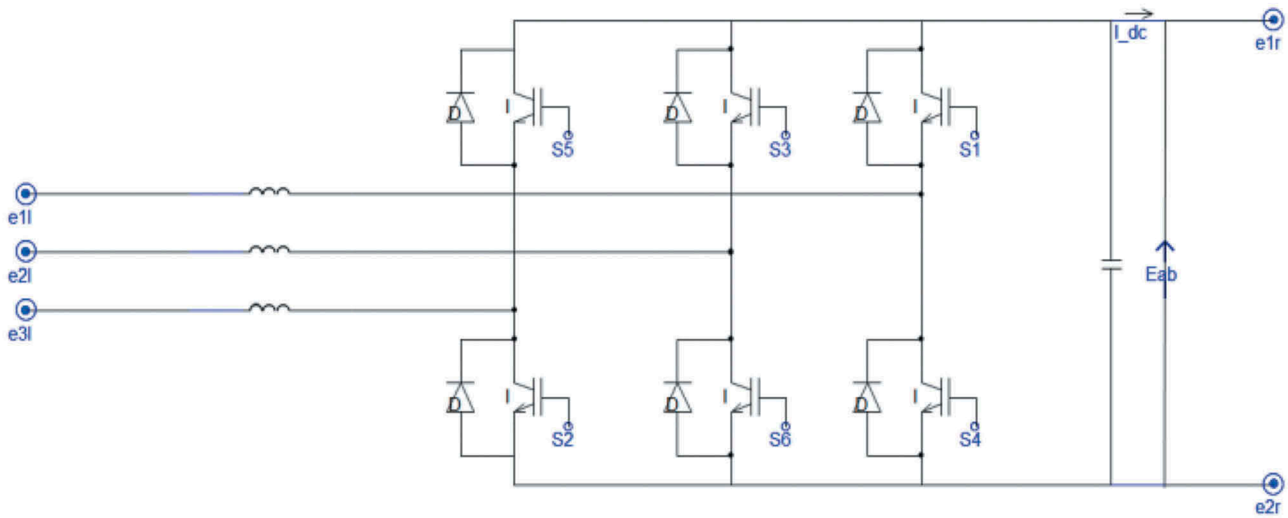

Figure 6. AC/DC Converter model.

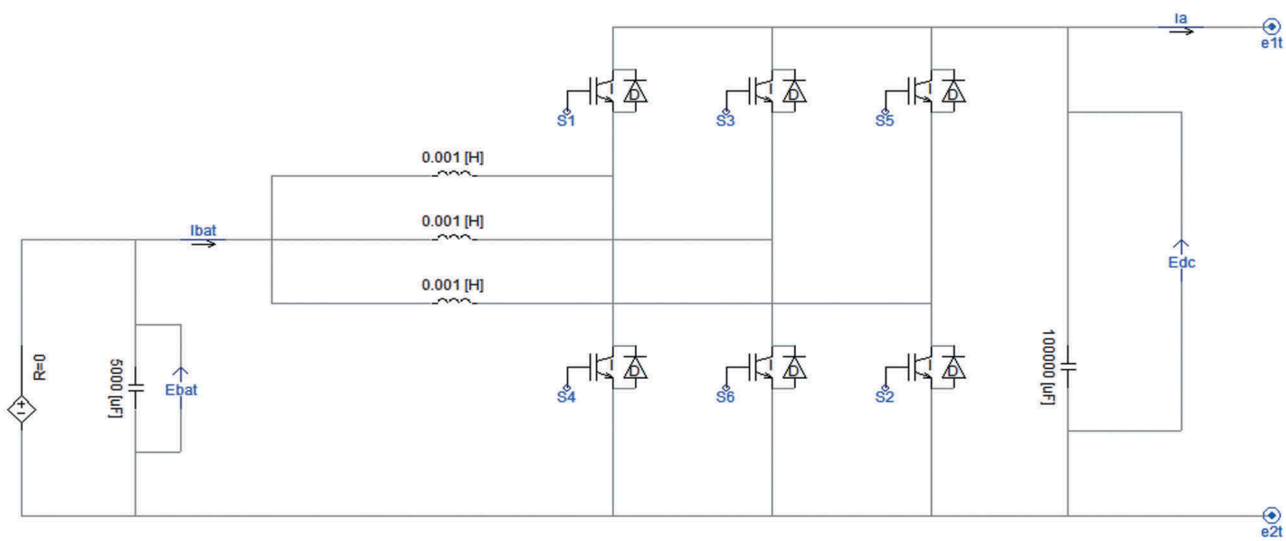

Figure 7. ESS model.

bypassed by three lower-side diodes. In the discharge mode, the IGBT switches of S2, S4, and S6 are switched and bypassed to the upper three diodes.

The ESS control method uses voltage and output control methods. In case of MAIN ESS, voltage control is performed to maintain a constant voltage of the DC microgrid. In case of SUB ESS, charge/discharge output control is conducted to adjust the power supply and demand of the DC microgrid; when the MAIN ESS is open due to failure or repair, the voltage control for maintaining the constant voltage of the DC microgrid is selectively performed [11].

2.2 DC microgrid operation method

In this study, we establish an algorithm based on the connection of MAIN ESS, power consumption of load, amount of power generation of distributed generator, and SOC of MAIN/SUB ESS. The algorithm determines the amount of charge/discharge of each component, control method, and output reference of the diesel generator according to the determined result. The operation mode in the modeled DC microgrid is largely divided into voltage and output control of ESS for DC bus voltage maintenance and power supply, connection of diesel generator, and output control method of distributed generator. The DC microgrid operates stably by controlling the three power sources.

2.2.1 Proposed energy management of DC microgrid

In this study, the energy management method of the DC microgrid can be divided into 12 modes through the connection of MAIN ESS, power consumption of the load, power amount of generation by distributed generator, and SOC of the MAIN/SUB ESS. Depending on each mode, the control method of the ESS and distributed generator, amount of charge/discharge, and input of the diesel generator are determined. Table 2 presents the divided operation modes according to the measurement situation. In case of the SOC of ESS, when the power supply of the distributed generator is larger than the power consumption of the load, on the basis of maximum 80% and minimum 20%, ESS charges when the maximum charge amount does not exceed 80%. If the ESS is not less than 20% of the maximum discharge amount then the discharge is continued. A threshold is given to each mode change algorithm step to avoid frequent mode changes due to sensor errors and ripples, and the algorithm is shown in Figure 8.

The modes in Table 2 are divided into three parts, namely, a comparison between the power supply of the distributed generator and the amount of power consumption of the load, the connection state of the MAIN ESS, and the SOC of each ESS.

A. P_{LOAD}, P_{PV}: Whether surplus power is generated can be determined by comparing the supply power of the distributed generator and the power consumption of the load. When surplus power exists, the ESS must be charged or the output of the distributed generator must be controlled.

B. MAIN ESS connection: This connection is important because MAIN ESS plays a key role in maintaining constant DC bus voltage. When MAIN ESS is disconnected due to failure or repair, the SUB ESS performing output control performs voltage control.

C. SOC: The SOC is determined by comparing the SOC of each MAIN/SUB ESS. The comparison of the SOC reference value is based on 80% of the maximum charge allowable value and 20% of the maximum discharge allowable value.

3. Simulation

In this study, we model and simulate a DC microgrid using PSCAD/EMTDC software. The simulation is conducted in two cases depending on whether to connect the MAIN ESS. In addition, we simulate a stable DC microgrid operation by changing the load and SOC with time, as shown in Table 3.

Cases 1 and 2 start with a SOC of 20%. In case 1, given that MAIN ESS is connected, SUB ESS provides output control to supply power to the load. The diesel generator is connected according to the power generation amount of the SOC and the dispersed power source; thus, the power balance of the DC microgrid is adjusted. In case 2, SUB ESS performs voltage control instead of MAIN ESS due to dropout of voltage control; thus, the voltage of the DC bus terminal is controlled constantly. The diesel generator is connected according to SOC and the generation power amount of the distributed generator, and the power balance of the microgrid is adjusted.

4. Conclusion

In this study, a DC microgrid is modeled by using PSCAD/EMTDC. For a stable power supply, the proposed algorithm is applied depending on whether to connect the MAIN ESS, power consumption of load, generation power of distributed generator, and SOC of MAIN/SUB ESS. The charge/discharge amount of each ESS, the control method, and the connection of the diesel generator are

Table 2. Proposed operation mode of DC microgrid.

MODE	P V MODE	Diesel connect	MAIN_ESS SUB_ESS	P_{SUB_ref}	DC BUS CONTROL UNIT
1	MPPT	DISCONNECT	Charge/Charge	P_{SUB_MIN}	MAIN_ESS
2	MPPT	DISCONNECT	Charge/Discharge	$P_{MAIN\_RATED} - P_{PV} + P_{LOAD}$	
3	MPPT	DISCONNECT	Discharge/Charge	$P_{PV} - P_{LOAD}$	
4	P control	DISCONNECT	Discharge/Discharge	P_{SUB_RATED}	
5	MPPT	CONNECT	Charge/Charge	$P_{PV} - P_{LOAD} + P_{MAIN\_RATED}$	
6	MPPT	DISCONNECT	Charge/Discharge	P_{SUB_RATED}	
7	MPPT	DISCONNECT	Discharge/Charge	P_{SUB_RATED}	
8	MPPT	DISCONNECT	Discharge/Discharge	$P_{LOAD} - P_{PV}$	
9	MPPT	DISCONNECT	Open/Charge	Voltage Control	SUB_ESS
10	P control	DISCONNECT	Open/Discharge		
11	MPPT	CONNECT	Open/Charge		
12	MPPT	DISCONNECT	Open/Discharge		

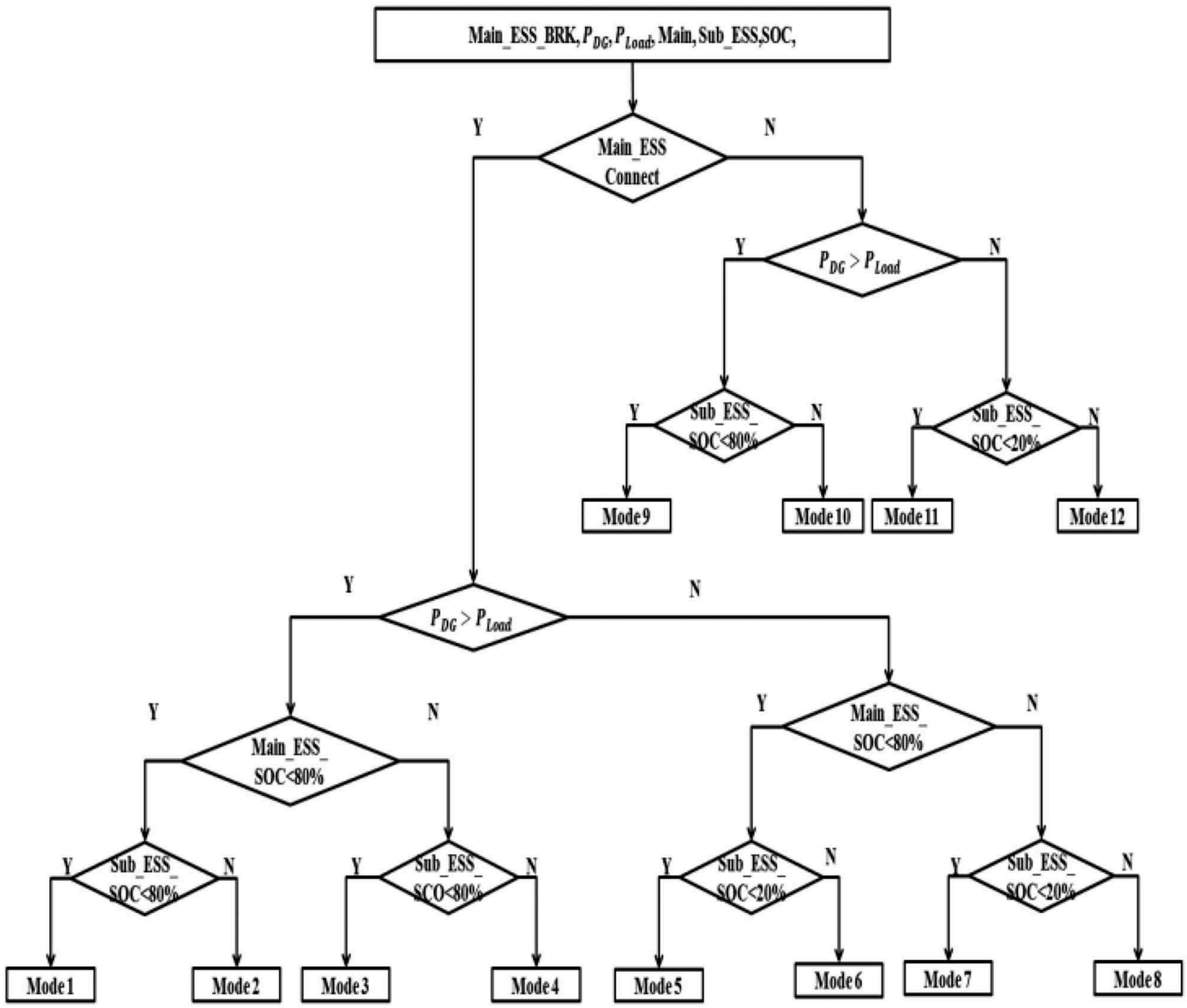

Figure 8. Proposed operation algorithm of DC microgrid.

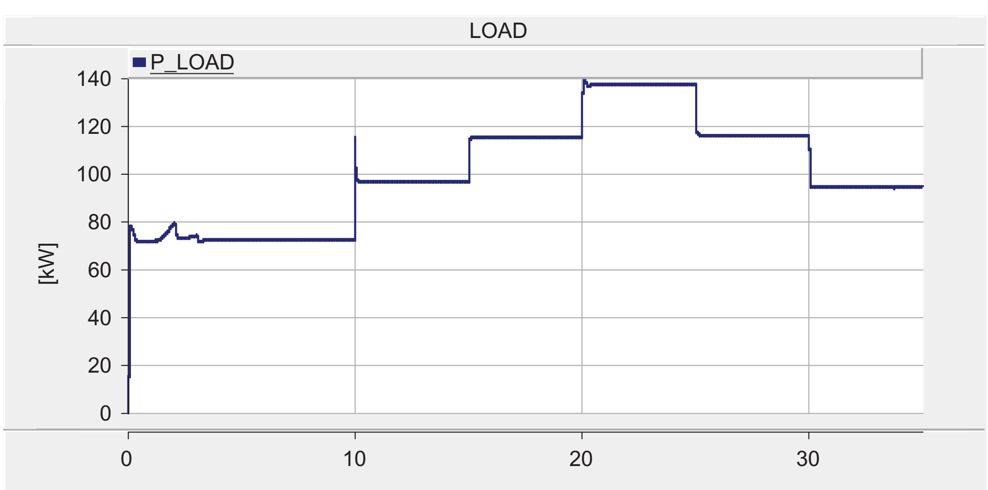

Figure 9. Power of DC loads.

Table 3. Simulation setting of MAIN ESS and load.

				ESS SOC	
CASE	MAIN ESS	TIME	LOAD	MAIN	SUB
1	CONNECT	0s	75kW	20%	20%
		10s	100kW	45%	23%
		15s	125kW	80%	25%
2	DISCONNECT	20s	150kW	60%	45%
		25s	125kW	45%	80%
		30s	100Kw	25%	60%

determined according to the mode determined by the algorithm. As a result, Figure 9 shows the power of DC loads, Figures 10 and 12 show the power flow according to the algorithm proposed in cases 1 and 2. Figure 11 shows that the voltage at the load side of case 1 is kept constant at a maximum of 1.03 p.u. and a minimum of 0.957 p.u. As shown in Figure 13, SUB ESS maintains a constant voltage maximum of 1.037 p.u. and a minimum of 0.955 p.u. by performing voltage control even if MAIN ESS, which performs voltage control, is disconnected. We propose a stable operation method of the DC microgrid through power control. However, the voltage drops due to the distance, and the low power supply will be studied and applied to the secondary control method considering the power line in the future.

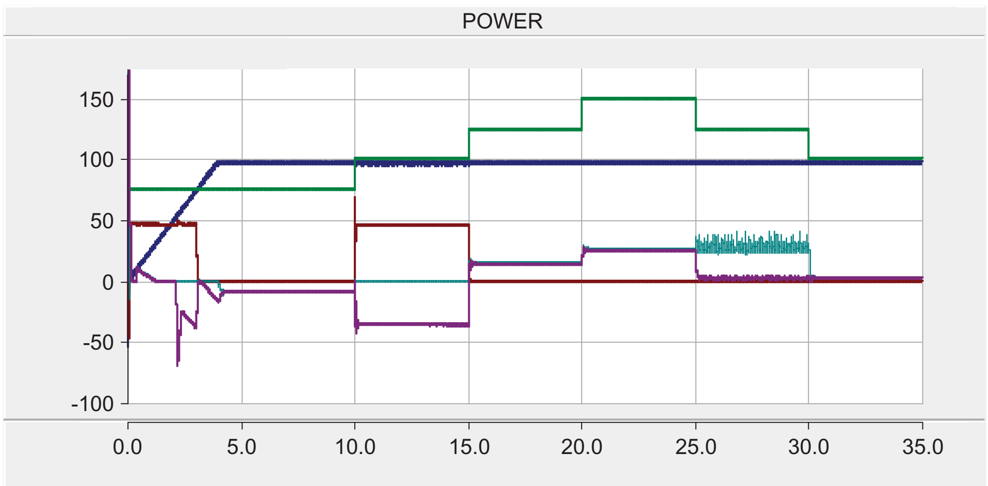

Figure 10. Case 1 Power flow of each component of DC microgrid.

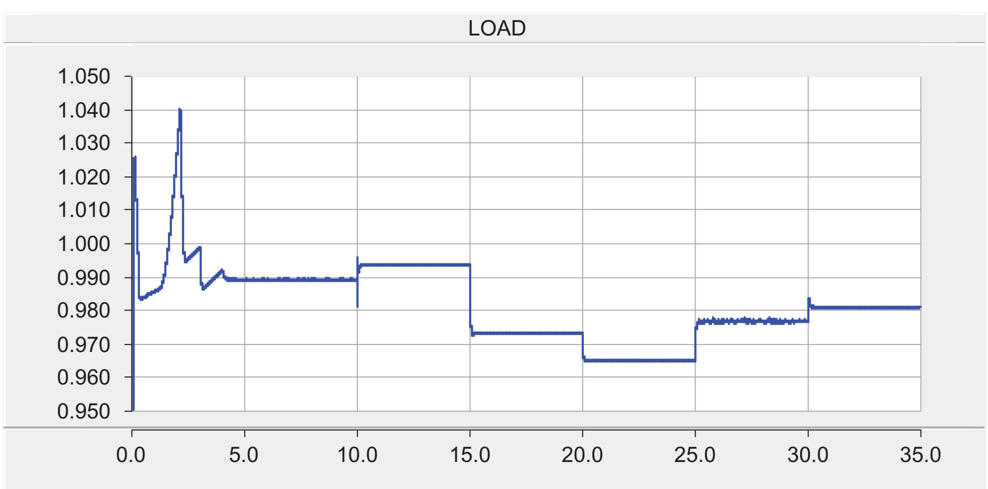

Figure 11. Case 1 Load-side voltage (p.u.).

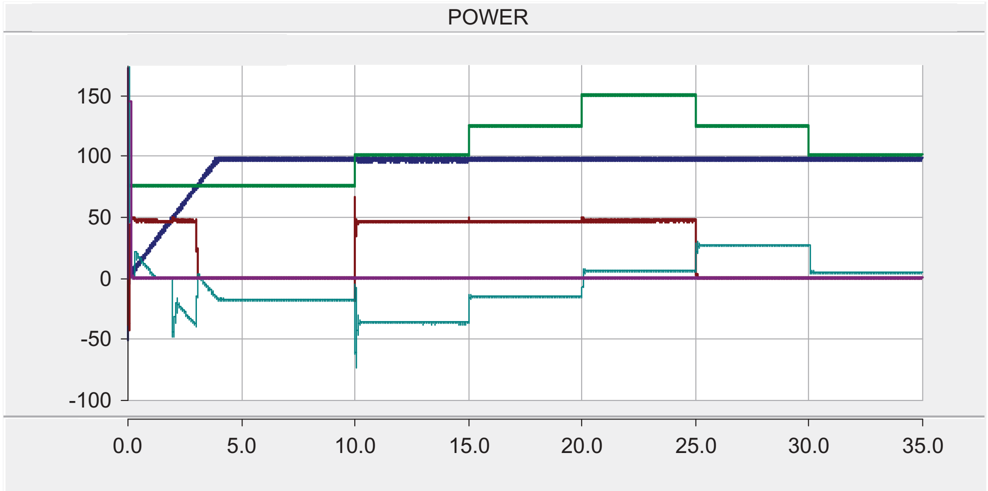

Figure 12. Case 2 Power flow of each component of DC microgrid.

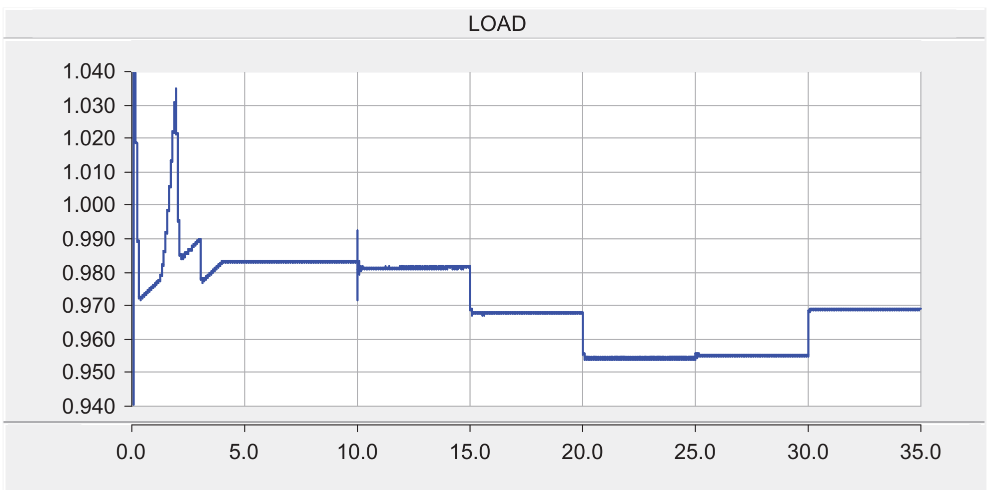

Figure 13. Case 2 Load-side voltage (p.u.).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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