J Electr Eng Technol.2018; 13(3): 1123-1130
http://doi.org/10.5370/JEET.2018.13.3.1123

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Study on the Voltage Stabilization Technology Using Photovoltaic Generation Simulator in Three-Level Bipolar Type DC Microgrid

Taehoon Kim*, Juyong Kim, Jintae Cho** and Jae-Seung Jung†**

Abstract – Voltage stabilization is an essential component of power quality in low voltage DC (LVDC) microgrid. The microgrid demands the interconnection of a number of small distributed power resources, including variable renewable generators. Therefore, the voltage can be maintained in a stable manner through the control of these distributed generators. In this study, we did research on the new advanced operating method for a photovoltaic (PV) simulator in order to achieve interconnection to a bipolar LVDC microgrid. The validity of this voltage stabilization method, using the distributed generators, is experimentally verified. The test LVDC microgrid is configured by connecting the developed PV simulator and DC load, DC line, and AC/DC rectifier for connecting the main AC grid. The new advanced control method is applied to the developed PV simulator for the bipolar LVDC grid in order to stabilize the gird voltage. Using simulation results, the stabilization of the grid voltage by PV simulator using the proposed control method is confirmed the through the simulation results in various operation scenarios.

Keywords: Photovoltaic generation, PV simulator, DC micro-grid, Grid voltage stabilization, Three-level bipolar grid.

1. Introduction

Most of the energy currently used is obtained from fossil fuels such as oil, natural gas, and coal. Furthermore, in the South Korea, the supply of most of such fuels is dependent on imports. While using fossil fuels, the greater the amount consumed, the greater the emissions of pollutants and carbon dioxides. Since the increase in atmospheric carbon dioxide has become a principal cause of the acceleration of global warming, which is currently a major global issue, a variety of renewable energy resources have been proposed as an appropriate solution to these problems through research conducted in the recent past [1, 2].

At present, solar energy, wind power, etc. are well known as the renewable energy resources, and variable sustainable developments related to their practical application are in progress. The electrical power from these resources is preferentially converted into DC, then into the AC again, in order to be linked to the commercial AC power distribution system. In this conversion process, additional converter facilities are required, thus incurring additional energy losses. Consequently, it limits the economic operation of renewable energy resources linked to a microgrid [3].

A microgrid is a type of electric power distribution system with a total capacity of several kW ~ MW class, Moreover, it is the most effective method for utilizing renewable energy as distributed power generators in parallel [4-9].

Furthermore, a microgrid has a number of advantages such as linking with a variety of renewable energy resources, when it has a low voltage DC (LVDC) power distribution configuration. The output power of the renewable generator may be DC type or not. As previously mentioned, the conversion process to DC is required in general before the conversion to commercial AC, if this power has to be linked with an existing AC distribution grid. However, the re-conversion process to AC can be omitted in the case of connection with the LVDC distribution grid. Therefore, it is possible to achieve the economic generation especially in the distribution of small-scaled renewable energy resources, by eliminating the loss of energy and additional equipment in re-conversion process. Furthermore, the LVDC microgrid offers significant advantage over of the single typed generator due to its interconnection with variable typed renewable generators. Moreover, nowadays, nearly all electronic devices used in a home environment require DC not AC power. Therefore, from an engineering and an economical perspective, LVDC power distribution system would be more useful and efficient than AC system [10, 11].

In South Korea, the demonstration site for the bipolar type ±750 V LVDC power distribution grid has been undergoing construction by KEPRI(Korea Electric Power Research Institute, Korea Electric Power Corporation) since 2016. An effective control algorithm for operating the LVDC microgrid-type grid will be developed at this site.

† Corresponding Author: Dept. of Electrical Engineering, Kyungpook National University, Korea.(bucstual@naver.com)
* Basic Electric Power Research Center, KEPCO, Korea. (nobleman@kepco.or.kr)
** Smart Power Distribution Lab., KEPRI, Korea. (juyong.kim@kepco.co.kr)
Received: August 16, 2017; Accepted: February 1, 2018

For the LVDC microgrid demonstration, many renewable generators have to be interconnected to the test site. However, most of the current studies for renewable energy generators widely used to distributed power are for the maximum power point tracking (MPPT) control, or interconnection to an AC power grid. Therefore, further research is required to achieve the interconnection of the renewable energy generator to the LVDC microgrid [12-13]. This paper presents the operating characteristics of the PV simulator, for interconnection to a bipolar ±750 V LVDC microgrid. Also, through experiments, we have demonstrated bipolar power valance control and voltage stabilization algorithm using this renewable generator. This PV simulator is scheduled to be a component consisting the demonstration site under construction.

2. Experimental LVDC Micro-grid

As shown in Fig. 1, the PV simulator developed by KEPRI is connected in the test bipolar ±750 V LVDC microgrid and all experiments are performed in the TEST-BED (Daejeon, South Korea) in KEPRI. The experimental DC microgrid consists of controllable components such as a 50 kW PV simulator (developed in this research), a 50 kW artificial DC load, two artificial DC lines, and a 50 kVA rectifier tied to the main AC grid. A bidirectional

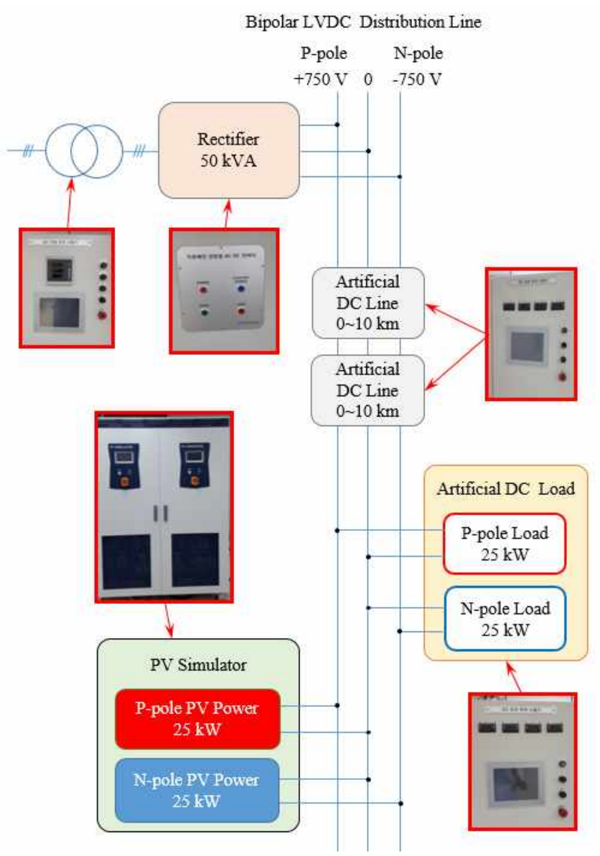


Fig. 1. Configuration of the Experimental set-up

three-phase AC/DC converter is used as grid-tied converter for reverse transfer of the DC dump power. All LVDC grid components are divided into two block (P-pole: +750 V and N-pole: -750 V parts) for matching with bipolar type LVDC grid, as shown in Fig. 2: block diagram of the PV Simulator.

PV simulator is based on the general single diode model of the PV array module. The general current-voltage characteristic of a PV model is expressed by the following formula (1) [14];

$$
\begin{aligned}
I &= I_{ph} - I_0\left(e^{\frac{V+R_S I}{V_t A}} - 1\right) - \frac{V+R_S I}{R_{sh}} \\
V_t &= N_s kT/q \\
I_{ph} &= \left(I_{ph,n} + K_I \Delta T\right)\frac{G}{G_n}, \ \Delta T = T - T_n \\
I_o &= \frac{I_{SC,n} + K_I \Delta T}{e^{\left(\frac{I_{SC,n}+K_V\Delta T}{AV_t}\right)} - 1}
\end{aligned} \tag{1}
$$

I_{ph}: photo-generated current in standard test condition (STC)
I_o : dark saturation current in STC
V_t : junction thermal voltage
R_s : panel series resistance
R_{sh} : panel parallel resistance
A : diode ideality factor
N_s : number of series cells
K : Boltzmann's constant
q : charge of electron
T : temperature
T_n : temperature in STC
G : irradiance
G_n : irradiance in STC
I_{SC} : short circuit current
V_{OC} : open circuit voltage
K_V : open circuit voltage temperature coefficient
K_I : short circuit current temperature coefficient

The PV simulator consists of a PV array module simulator unit and a PV converter unit as shown in Fig. 3.

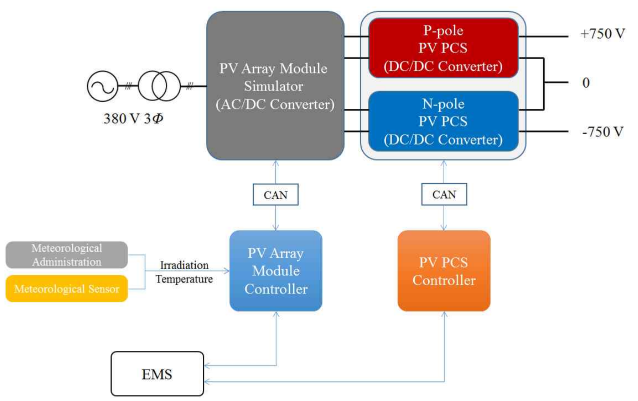


Fig. 2. Block diagram of the PV simulation system developed for bipolar LVDC distribution grid

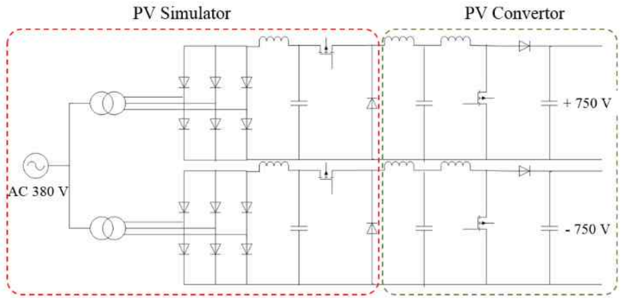


Fig. 3. Circuits of PV simulator and convertor used in the experiments

Owing to the solar cell characteristics and weather information, the PV array module simulator unit transfers the DC power (DC voltage and current) to the next PV converter unit. The buck converter is used because the output voltage is lower than the input voltage from the three-phase 380 V AC grid and rectifier. On the other hand, the boost converter is used as a PV converter, in order to increase the input voltage from the buck converter to the LVDC grid voltage of ±750 V.

This simulator used is designed to carry out various experiments for developing new renewable energy source operation algorithm. For this purpose, the PV simulator part and the converter part can be separated, and the output capabilities of these parts are designed to have a margin. The output of the PV simulator and the converter can be controlled and limited programmatically and individually.

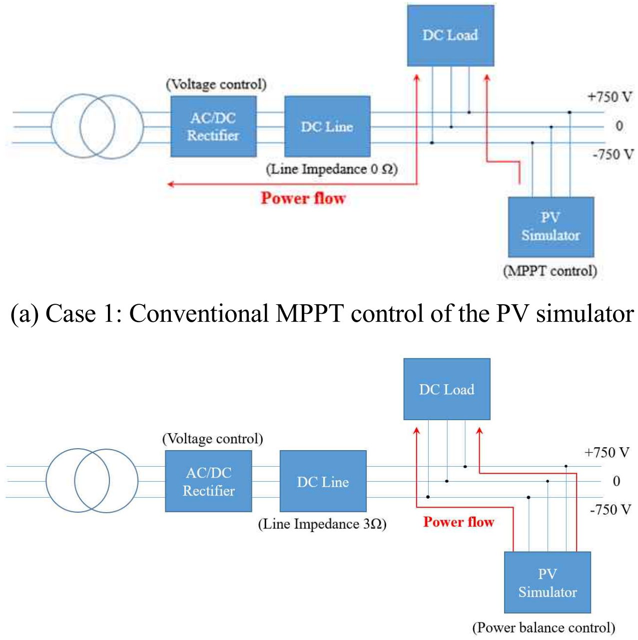
3. Control Method of LVDC Micro-grid

3.1 Power flow

The Power flow of the components of the LVDC microgrid is shown in Fig. 4. The distributed generators such as the PV simulator in the experimental microgrid, supply unidirectional power to LVDC microgrid, and play a role as main energy source. Moreover, the distributed generators control the power balance of DC microgrid by the individual output power control at P-pole and N-pole.

In case 1, when the energy is generated from PV generator by MPPT control, excessive power is supplied to or obtained from AC grid through the bidirectional inverter, as shown in Fig. 4(a). In this case, the rectifier has a voltage control. In the case 2, when the energy exchange with the AC grid is impossible, and the load depends entirely on the PV generator output, PV generator operates under a power balance control, as shown in Fig. 4(b). According to a varying load demand, PV generator needs to realize a power balance between poles, and thus it achieves a continuous high-quality power supply to DC load.

In case 1, the PV simulator is operated as a conventional PV generator with MPPT control. However, in case 2, the PV simulator has a role as a power balance control between the poles, responding to the change of the load in bipolar LVDC microgrid. In this case, the PV generator will supply power according to the status of each pole without power from the battery or the AC grid.



(a) Case 1: Conventional MPPT control of the PV simulator

(b) Case 2: Power balance control by the PV simulator)

Fig. 4. Power flow of each component at the each case

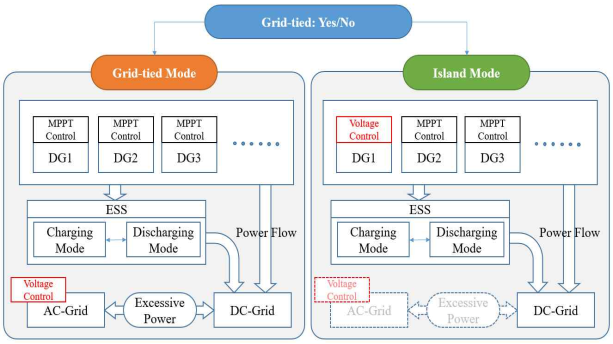
3.2 Conventional power control method

The conventional power control method is classified as a grid-tied mode and an islanded mode. A grid-tied converter has a control about LVDC grid voltage in the grid-tied mode, and distributed generators have the control in the islanded mode. In this experiment, ordinary energy storage elements are not inserted into the test LVDC microgrid.

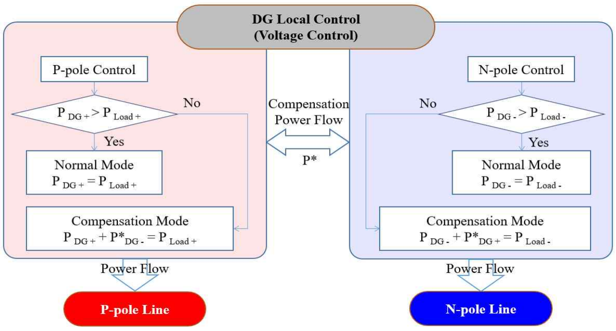
Paradigmatically, in the grid-tied mode, power management is performed in a complementary manner between distributed generators and AC grid. The LVDC microgrid can then operate safely and efficiently, as shown in Fig. 5 (a). If output sum of the distributed generators are able to supply sufficient power to the DC loads, excessive power is supplied to the AC grid. If the power sum of the distributed generators is insufficient to the load demand, lack of power is supplied from the AC grid [15].

Due to the ordinary concept of the power control method in the island mode, it is operated when LVDC microgrid is separated from AC grid. In this mode, grid-tied converter released a control over the LVDC grid voltage, and one of converters of the distributed generators must take over the control. Furthermore, because each converter of distributed generators is used for an optimal control of each generator, only the converters of energy storage elements can afford to regulate the LVDC grid voltage.

During the island mode, the energy storage elements can play a role in regulating LVDC grid voltage in response to a sudden power requirement, as an auxiliary converter. Therefore, the power capability of the energy storage elements can achieve significant capacity in the island mode [16-18].



(a) Conventional power management method



(b) Power balance control between poles

Fig. 5. Control concept of the LVDC micro-grid

3.3 Power balance control between poles

The bipolar LVDC distribution grid has an ability to transmit power through the two pole lines. The change of each load connected in each pole can, therefore, cause an imbalance in the load. In the grid-tied mode, this can be compensated by the grid-tied converter. However, if the microgrid is operated in the island mode, the grid voltage fluctuation may occur in only one pole. A simple way to solve this problem is to use an energy storage element. However, its lifetime and cost can be a significant impediment to economical operation. In this study, we try to reduce the energy storage element dependence on the voltage stabilization and obtain it in the bipolar LVDC grid through the individual control of each pole and the power transfer between the poles of PV simulator, as shown in Fig. 5(b).

This power control method in Fig. 5(b) is to control two poles separately under the PV rating power, which allow the extra power to be supplied to the pole with insufficient power to stabilize the grid voltage.

4. Experimental Results and Discussion

4.1 Experimental cases

In order to verify the proposed power management method of the LVDC microgrid, an experiment is performed using the PV simulator developed for bipolar type LVDC grid. The experimental DC microgrid is operated in the grid-tied mode, and variable grid situations are adopted to verify the proposed power management

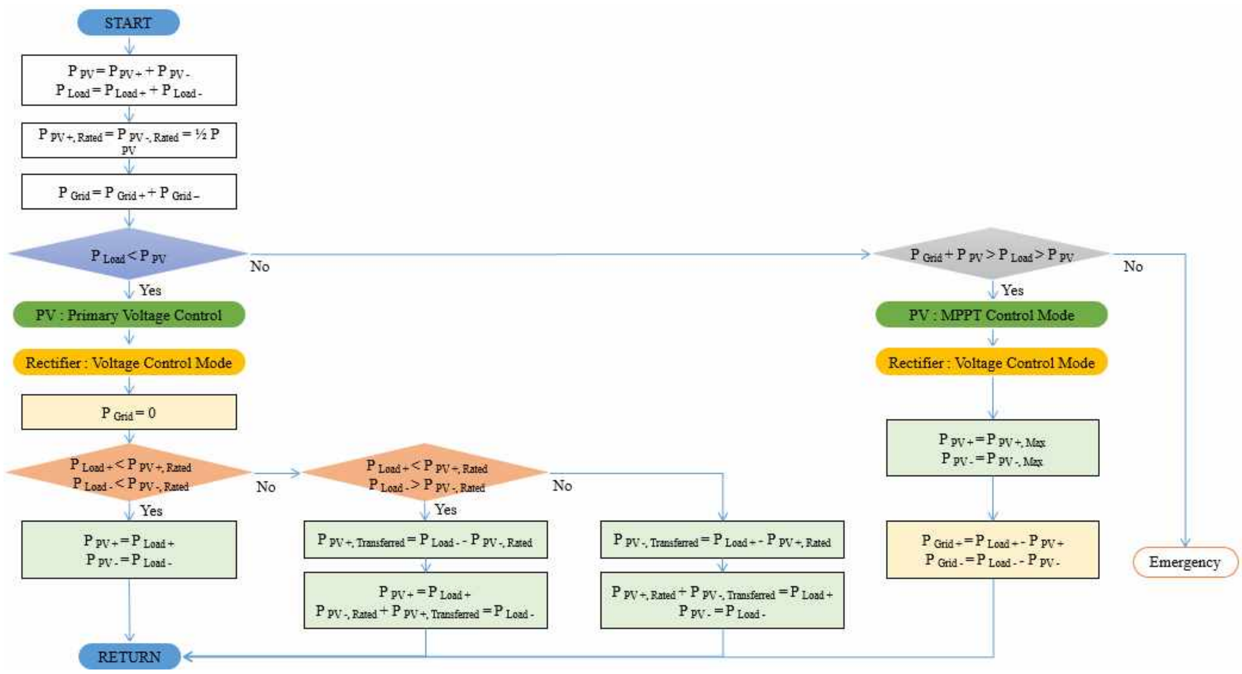


Fig. 6. Flowchart of the power balance control between poles

Table 1. Experimental case details

No.	Mode	Details
Case 1	Conventional power control	When grid-tied situation is normal; Bidirectional converter: voltage control PV simulator: MPPT control with information of Meteorological Administration
Case 2	Power balance control between poles	When extra power transmission to/from grid is impossible; 1) Case 2-1 $P_{Load} < P_{PV}$, Independent control mode in each pole Power compensation mode for lack of the one pole 2) Case 2-2 $P_{Load} > P_{PV}$, Uncritical load is disconnected.

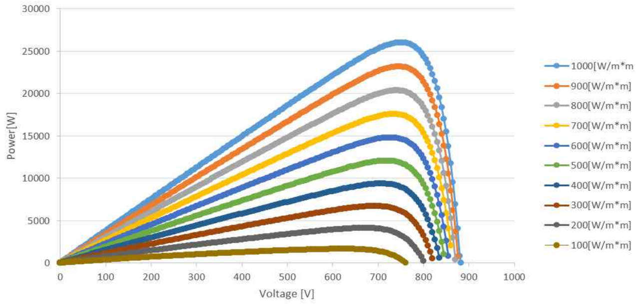
method, as listed in table 1. The operating mode in the experiment is scheduled in terms of the varying load demand and time. To verify the operation of the PV, energy storage elements are ignored.

In the power balance control between poles, as shown in Fig. 6, the battery does not respond to the change in the load, but the PV is directly burdened by the change. When the PV power is greater than the load power, the PV power can respond to the load power through voltage control rather than MPPT control. In the event of a load imbalance problem, the P-pole and N-pole of the PV simulator are controlled independently within 25 kW, in order to maintain grid voltage stabilization. If more than 25 kW of power is required at load of one pole, the surplus power at the other pole can compensate it**.**

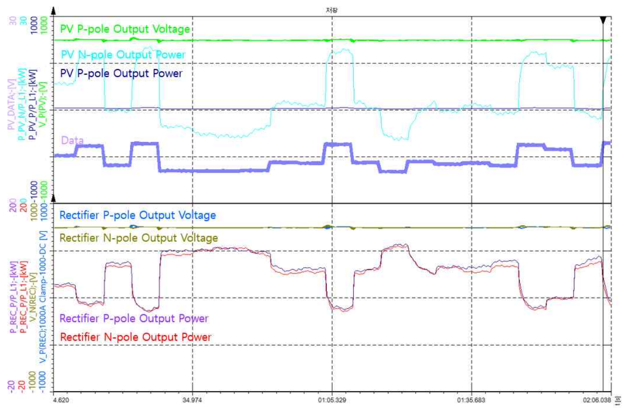
4.2 Experimental result analysis

Fig. 7 is an experimental result of case 1, when the ordinary control mode exhibits power fluctuation (total experiment time: 6 minutes) of the PV simulator under MPPT control, and information from the Meteorological Administration. The output of PV varies according to the PV array module specifications and irradiation/temperature data. Moreover, corresponding converters operate using the MPPT method. Fig. 7(a) shows P-V curve of the PV array module applied in this experiment. Fig. 7(b)-(d) show the PV power and bidirectional converter power, when the DC load demands 40 kW. If the power generated by the PV simulator exceeds the power demanded by the load, excessive power is transferred to the grid through the bidirectional converter. On the order hand, if PV Power is below the load demand, a shortage of power is transferred from the grid. In this case, the grid converter has voltage control.

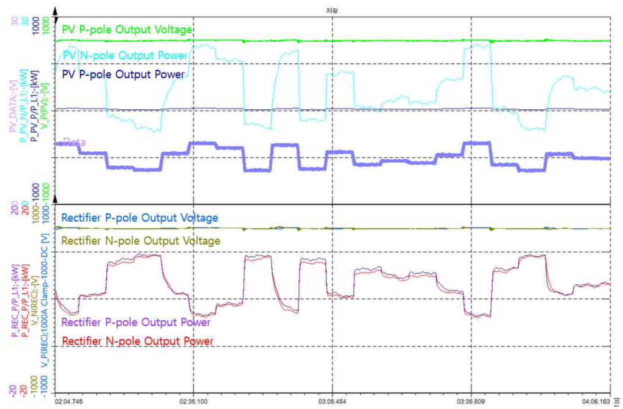
Grid voltage stabilization is the most important issue in the LVDC distribution system. Furthermore, in the microgrid connected with variable renewable generators used as decentralized power sources, it would be the most important issue because of the instability of renewable resources. Therefore, the LVDC microgrid requires an energy storage system (ESS) with sufficient capacity.



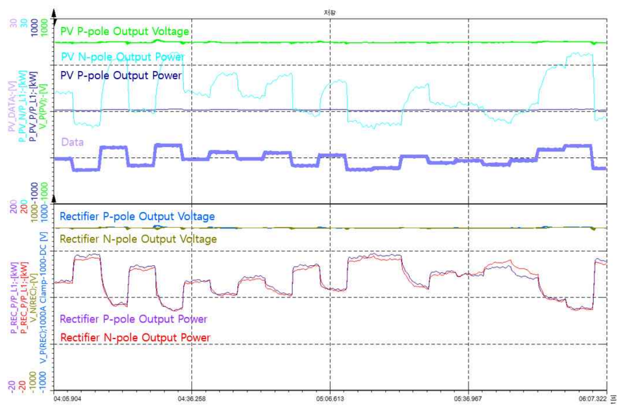
(a) *P-V* curve



(b) t = 0~120 s

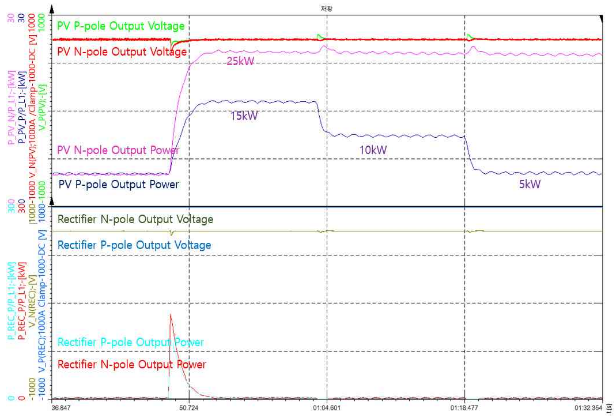


(c) t = 120~240 s

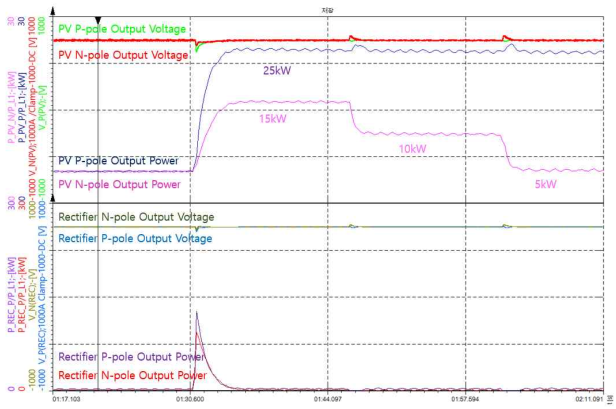


(d) t = 240~360 s

Fig. 7. Ordinary control of PV array in grid-tied case (Basic MPPT model by P&O control algorithm)



(a) Load variation in P-pole and fixed load in N-pole



(b) Load variation in N-pole and fixed load in P-pole

Fig. 8. Micro-grid voltage stabilization by independent voltage control of P and N-poles of the PV simulator in the single pole load variation

Table 2. Microgrid voltage variation in the single-pole load variation

Time [sec]	P-pole grid			N-pole grid		
	Load [kW]	Grid Voltage [V]	Voltage Variation Rate[%]	Load [kW]	Grid Voltage [V]	Voltage Variation Rate[%]
0~15	15	748.5	0.20	25	747.6	0.32
15~30	10	748.7	0.17	25	746.9	0.41
30~45	5	748.9	0.15	25	746.8	0.43
0~15	25	748.1	0.25	15	748.0	0.27
15~30	25	748.2	0.24	10	747.6	0.32
30~45	25	748.1	0.25	5	747.8	0.29

However, such a system demands a very high cost per kW unit, as mentioned earlier.

If there is an issue in the grid, the grid cannot respond to the excess power or lack of power in the microgrid. This case would be relevant to accidents in main grid. In this case, a change in the grid voltage occurs depending on the change of the load power and the PV power, and an ESS (battery) is generally used to resolve this problem. That is, the battery is burdened with the fluctuation in load, which affects the life of the battery.

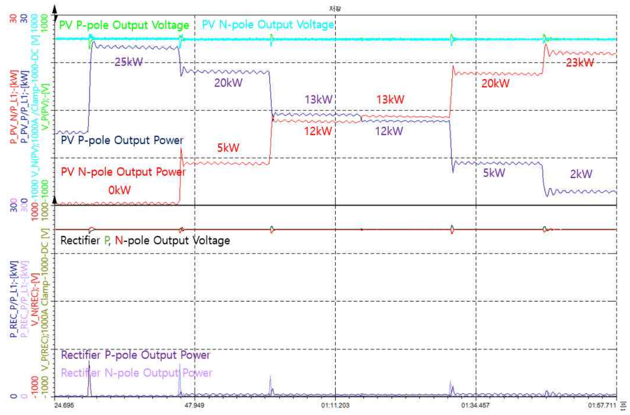


Fig. 9. Micro-grid voltage stabilization by independent voltage control of P and N-poles of the PV simulator in the two-pole load simultaneous variation (including mono-pole operation)

Table 3. Microgrid voltage variation in the two-pole load simultaneous variation (including mono-pole operation)

Time [sec]	P-pole grid			N-pole grid		
	Load [kW]	Grid voltage [V]	Voltage variation rate [%]	Load [kW]	Grid voltage [V]	Voltage variation rate [%]
0~15	25	747.4	0.35	0	752.7	-0.36
15~30	20	748.5	0.20	5	747.3	0.36
30~45	13	748.5	0.20	12	747.5	0.33
45~60	12	748.5	0.20	13	747.7	0.31
60~75	5	749.7	0.04	20	746.1	0.52
75~90	2	749.0	0.13	23	746.5	0.47

Fig. 8 and Table 2 show experimental results for the grid voltage stabilization by the independent voltage control of the P and N-pole of the PV simulator in the single pole load variation. When one pole load requires the regular power of 25 kW, another pole load changes step by step. In the results, grid voltage is kept constant at ±750 V, regardless of the load variation and the imbalance between the two pole loads. Moreover, voltage variation rate is under the 1%, and is calculated using the following formula (2);

$$\text{Votage Variation Rate} = \frac{750\,V - \text{Grid Voltage}}{750\,V} \times 100[\%] \quad (2)$$

Fig. 9 and Table 3 show experimental results for the grid voltage stabilization in the double pole load variation. When the load fluctuations of the two poles are mutually independent, including the mono pole operation, the grid voltages of the two poles are kept constant at ±750 V. The voltage variation rate is also under the 1% in this case. In this experiment, total output power is fixed under 25 kW, and the maximum power of one pole is basically 12.5 kW

($P_{PV, Rated}$). If a load on one pole requires more than this value, PV simulator can compensate for it by using the surplus power on the other pole. Essentially, that is to reduce the output power for the low-load pole, and increase the output power for high-load pole. The compensation power, P^*_{Load} are determined by following formula (3), (4);

P-pole compensation: $P^*_{Load+} = P_{Load-} - P_{PV-,Rated}$ (3)

N-pole compensation: $P^*_{Load-} = P_{Load+} - P_{PV+,Rated}$ (4)

Since the test microgrid does not involve a battery, output power of the grid-tied converter appears in the transient region as shown in Fig. 8 and Fig. 9. If it is an actual island, the battery will have to assist in the transient region.

5. Conclusion

In this study, the operating characteristics of the PV simulator developed for the bipolar LVDC grid were investigated. The experimental results verified that distributed generators such as PV simulator can be controlled to stabilize the voltage of the LVDC microgrid. The test LVDC microgrid was configured by connecting the developed PV simulator, DC load, DC line, and AC/DC rectifier for connecting the main AC grid. A new power balance control between poles was applied to developed PV simulator for the bipolar LVDC grid, in order to stabilize the grid voltage. Furthermore, the simulation results validated that the proposed power management method ensures that the PV simulator stabilizes the grid voltage in the various operation cases. The developed PV simulator provides a basic research foundation for the bipolar LVDC microgrid control method, and it is extended to variable distributed generators connected to the microgrid. Furthermore, the outcomes will be utilized in a real scale demonstrative system.

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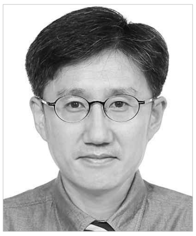
Taehoon Kim He received the B.S. and M.S degree from Kyungpook National University in 2005 and in 2007, respectively, and he is working toward Ph D in the area of DC distribution. He is currently a senior researcher at the KEPRI (Korea Electric Power Corp. Research Institute), Seoul, Korea. His main research interests of LVDC distribution system.



Juyong Kim He received the M.S. and Ph.D. degree from Kyungpook National University in 1994 and in 2007, respectively. He joined the KEPRI (Korea Electric Power Corp. Research Institute) as a researcher in 1994. His main research interests are DC distribution system and DC microgrid. He is currently a principal researcher at Smart Power Distribution Lab. of KEPRI.

Jintae Cho He received the B.S. and M.S. degrees in Electrical Engineering from Korea University, Seoul, Korea, in 2006 and 2008, respectively, and he is working toward Ph.D in the area of DC distribution. He is currently a senior researcher at Smart Power Distribution Lab. of KEPRI (Korea Electric Power Corp. Research Institute), Daejeon, Korea. His research interests include protection, monitoring and control of LVDC distribution system.

Jae-Seung Jung He received the B.S., M.S., and Ph. D. degrees in electrical engineering from Kyungpook National University, Korea, in 2004, 2007, and 2011, respectively. His research fields are the high voltage and power distribution system. He worked for in Korean Electrical and Science Research Institute, 2015-2016. He is currently a lecturer of Kyuungpook National University and is conducting research on high voltage.