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Power Flow Calculation Method of DC Distribution Network for Actual Power System

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Abstract

DC distribution system has been evaluated as an excellent one in comparison with existing AC distribution network because it needs fewer power conversion stages and the full capacity of the equipment can be used without consideration for power factor. Recently, research and development on the implementation of DC distribution networks have been progressed globally based on the rapid advancement in power-electronics technology, and the technological developments from the viewpoint of infrastructure are also in progress. However, to configure a distribution network which is a distribution line for DC, more accurate and rapid introduction of analysis technology is needed for the monitoring, control and operation of the system, which ensure the system run flexible and efficiently. However, in case of a bipolar DC distribution network, there are two buses acting as slack buses, so the Jacobian matrix cannot be configured. Without solving this problem, DC distribution network cannot be operated when the network is unbalanced. Therefore, this paper presented a comprehensive method of analysis with consideration of operating elements which are directly connected between neutral electric potential caused by the unbalanced of load in DC distribution network with bipolar structure.

Keywords: *DC Distribution System, Unbalanced Bipolar DC System, Power Flow Algorithm*

I. Introduction

The increase and spread of IT equipment in customer areas, such as building and home, electric home appliance, photovoltaic, and ESS have led the development and commercialization of LVDC distribution system, which can reduce power conversion loss and raise system efficiency. However, beyond the benefit from reducing loss, increase of large-scale data centers and infrastructure for charging electric vehicles, supply of renewable energy resource complex such as photovoltaic and wind power and distributed resource such as ESS caused demand for capacity increase of distribution system and efficiency improvement [1]-[3]. To address this situation, the development from LVDC to MVDC distribution system is in progress. In particular, technology development of MVDC equipment such as power conversion equipment and protection device is in progress and demonstration research for MVDC DC distribution is taking place at small island systems, campuses and airports [4]-[6]. However, most studies are on point-to-point DC systems which connect the current two points, and therefore, more research needs to be performed to connect and operate multiple pieces of equipment and to increase the capacity of the distribution network by securing the flexible operation of the distribution network [7].

DC distribution system has advantages such as fewer power conversion stages and full capacities of the equipment can be used without consideration for power factor in comparison with existing AC distribution network. Recently, research and development of DC distribution system have been progressed globally based on the rapid advancement in power-electronics technology. However, to configure a DC network for distribution system, more accurate and rapid introduction of analysis technology is needed for the monitoring, control and operation of the system, which ensure the system run flexible and efficiently. In particular, regarding the analysis technology, there are many challenges for applying many existing methodologies that have been used in the analysis of AC systems although phase is not considered as requirement [12][13].

In general, repetitive calculations using the Jacobian Matrix are used in the power flow calculation of a network. But, in case of a bipolar DC distribution network, there are two buses acting as slack buses, so the Jacobian matrix cannot be configured. To solve this problem, analysis methods separating network is used, with one having the positive pole and a neutral line and the other having the negative pole and a neutral line. These are methods assuming that the electric potential of the neutral line does not deviate much from 0 V because the magnitude and location of electric elements (load and generation) of the two systems are not different. However, it has a defect that analysis of electric elements which are connected between positive and negative poles is impossible because there is unbalance in the field, in which the actual DC distribution network is configured. Without solving this problem, solutions essential to the operation of the DC distribution network such as voltage control cannot be operated when the network is unbalanced [14][15].

Therefore, a comprehensive method of analysis even with consideration of operating elements which are directly connected between neutral electric potential caused by the unbalance of load

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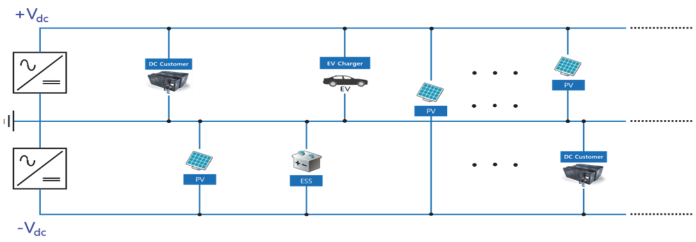

Fig. 1. Example of bipolar DC distribution network.

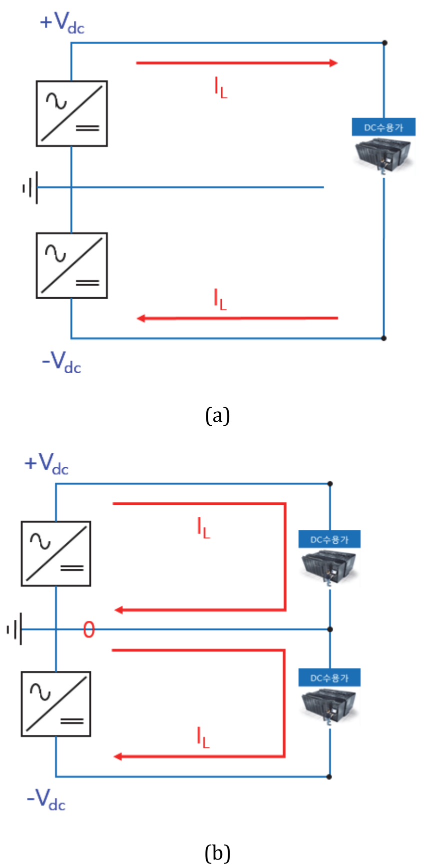

Fig. 2. A case without current on the neutral line.

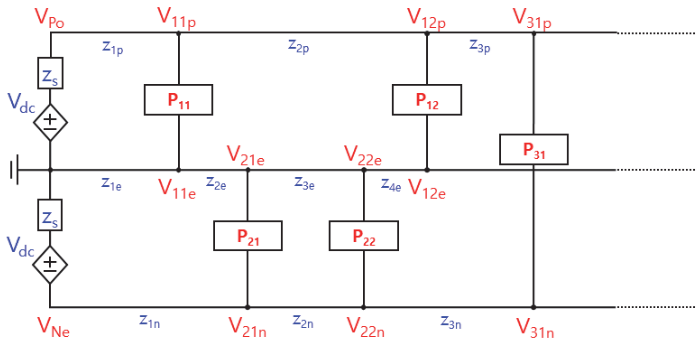

Fig. 3. Example of a DC distribution network for network analysis.

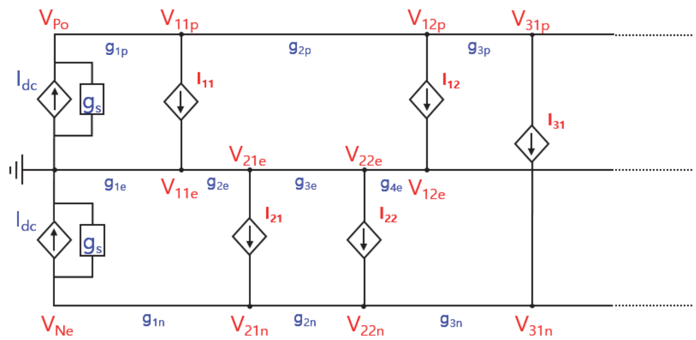

Fig. 4. Example of a DC distribution network converted into an equivalent model.

TABLE 1
Roles of Each Conductor by Connection Types to the Network

	Connection types		Feeder	Return path
Type 1	Positive	Neutral	Positive	Neutral
Type 2	Negative	Neutral	Neutral	Negative
Type 3	Positive	Negative	Positive	Negative

in DC distribution network with bipolar structure and negative pole is proposed in this paper. Also, simulation with the use of PSCAD/EMTDC and the measured values from the demonstration site were compared regarding power flow calculation method proposed in this paper.

II. Power Flow Calculation Method of DC System

In a bipolar DC distribution network, the network connection of loads or generators is formed with connections between positive pole and neutral line, neutral line and negative pole and positive pole and negative pole as shown in Fig. 1. Depending on the connection type, each conductor plays a role of feeder and return path as shown in TABLE 1.

If only the elements of Type 3 in bipolar DC distribution network are operated, or elements of Type 1 and Type 2 are operated with the same magnitude at the same location, the current of neutral line is 0 and all points of the neutral line do not have the electric potential. However, the network analysis taking in account the electric potential of the neutral line shall be performed because it cannot be always defined that loads only in Type 3 are operated or because loads of Type 1 and Type 2 does not always mean the operation status with the same magnitude at the same location.

It is assumed that there are electric elements with arbitrary location and magnitude connected to the bipolar DC distribution network and operated as shown in Fig. 3. From a viewpoint of the DC distribution network, an AC/DC converter can be modeled as a series circuit of a power impedance and DC voltage source, which creates electric potential difference between positive pole and neutral line, and between neutral line and negative pole. In performing circuit analysis in Fig. 3, simpler circuit equation can be derived by converting the source modeled as a voltage source into an equivalent current source, the impedance between nodes into conductance and the loads or outputs of generators into an equivalent current source as shown in Fig. 4.

Equation (1) is magnitude of equivalent current source of converter, which corresponds to the Norton equivalent current source. Equation (2) is conductance matrix for the equivalent network in Fig. 4. The current values of load and generator elements

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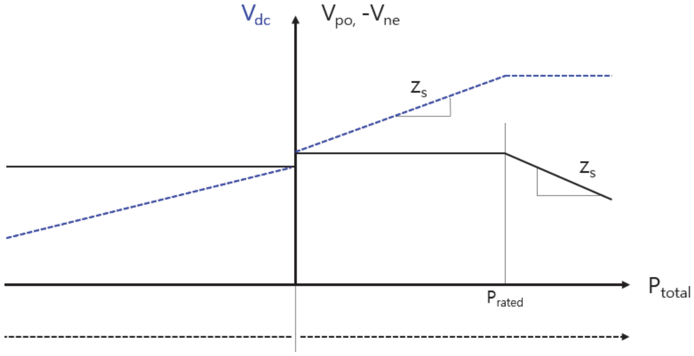

Fig. 5. Operation voltage compared with the output of the voltage source converter.

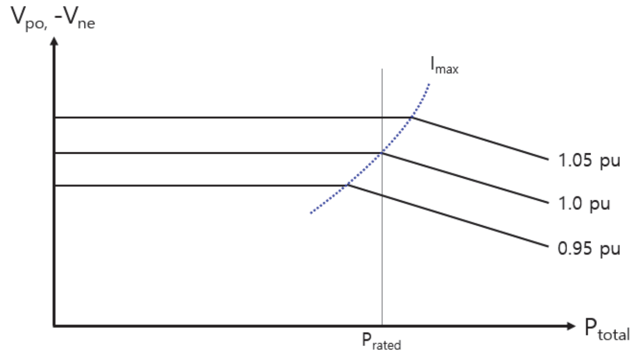

Fig. 6. Output voltage by operating voltage due to the maximum current limit.

$$I_{dc} = g_S \cdot V_{dc} \tag{1}$$

$$\begin{bmatrix} g_S+g_{1p} & 0 & -g_{1p} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & g_S+g_{1n} & 0 & 0 & 0 & -g_{1n} & 0 & 0 & 0 & 0 & 0 & 0 \\ -g_{1p} & 0 & g_{1p}+g_{2p} & 0 & 0 & 0 & 0 & 0 & -g_{2p} & 0 & 0 & 0 \\ 0 & 0 & 0 & g_{1e}+g_{2e} & -g_{2e} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_{2e} & g_{2e}+g_{3e} & 0 & -g_{3e} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & g_{1n}+g_{2n} & 0 & -g_{2n} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -g_{3e} & 0 & g_{3e}+g_{4e} & 0 & 0 & -g_{4e} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -g_{2n} & 0 & g_{2n}+g_{3n} & 0 & 0 & 0 & -g_{3n} \\ 0 & 0 & -g_{2p} & 0 & 0 & 0 & 0 & 0 & g_{2p}+g_{3p} & 0 & -g_{3p} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & g_{4e} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -g_{3p} & 0 & g_{3p} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -g_{3n} & 0 & 0 & 0 & g_{3n} \end{bmatrix} \begin{bmatrix} V_{po} \\ V_{ne} \\ V_{11p} \\ V_{11e} \\ V_{21e} \\ V_{21n} \\ V_{22e} \\ V_{22n} \\ V_{12p} \\ V_{12e} \\ V_{31p} \\ V_{31n} \end{bmatrix} = \begin{bmatrix} I_{dc} \\ -I_{dc} \\ -I_{11} \\ I_{11} \\ -I_{21} \\ I_{21} \\ -I_{22} \\ I_{22} \\ -I_{12} \\ I_{12} \\ -I_{31} \\ I_{31} \end{bmatrix} \tag{2}$$

$$I_{1i} = \frac{P_{1i}}{V_{1ip} - V_{1ie}} \quad \text{(Positive pole-to-Neutral Load)} \tag{3}$$

$$I_{2i} = \frac{P_{2i}}{V_{2ip} - V_{2ie}} \quad \text{(Neutral-to-Negative pole Load)} \tag{4}$$

$$I_{3i} = \frac{P_{3i}}{V_{3ip} - V_{3ie}} \quad \text{(Positive pole-to-Negative pole Load)} \tag{5}$$

here can be calculated like Eq. (3) to Eq. (5). These equations are used to update the current values of the elements in the process of repetitive calculation [16][17].

For AC distribution network, the circuit equation in Eq. (2) is used to derive the Jacobian matrix because voltage, current and phase angle are not completely linear with the magnitude of generation or load, which makes it impossible to obtain the solutions directly. However, there is no concept of phase angle in DC network and the status of the system with the node voltage can be analyze by simply solving the equation in Eq. (2).

However, only this analysis can apply for a converter which has characteristics that the V_{dc} output depends on loads. Provided that the use of voltage source converter such as constant voltage operation or variable operation is available, the following conditions should be considered to calculate the power flow: 1) For output voltage control of voltage source converter terminals, that is, for converter models which were modeled as equivalent power source, variable V_{dc} control function should be considered for controlled outputs for V_{po} and V_{ne}; 2) The range of internal voltage adjustment of the converter, that is, the range of load current in which the voltage control at the converter terminals is possible should be considered. Also, 3) Converter voltage under the condition of supply to the upper network, that is, if the generating power exceeds the loads in DC distribution network, the remaining power should be supplied to the upper network, and the converter operation voltage under such conditions should be considered.

III. Optimal Power Flow Analysis System for Biploar DC Distribution Networks

A. Proposed Power Flow Method for a Bipolar DC Distribution Network

In general, the operating voltage curve of constant voltage output of bipolar AC/DC converter is shown in Fig. 5. We can see that the internal voltage source generated by the converter to keep the converter terminal voltage of V_{po} and V_{ne} as constant voltage within the rated range increases linearly as the power output increases, and

$$Y'\begin{bmatrix} I_{dc} \\ -I_{dc} \\ V_{11p} \\ V_{11e} \\ V_{21e} \\ V_{21n} \\ V_{22e} \\ V_{22n} \\ V_{12p} \\ V_{12e} \\ V_{31p} \\ V_{31n} \end{bmatrix} = \begin{bmatrix} V_{po} \\ V_{ne} \\ -I_{11} \\ I_{11} \\ -I_{21} \\ I_{21} \\ -I\_22 \\ I_{22} \\ -I_{12} \\ I_{12} \\ -I_{31} \\ I_{31} \end{bmatrix} \tag{6}$$

$$Y' = \begin{bmatrix} a_{11} - a_{i1}a_{i1} & \cdots & a_{1i-1} - a_{1i}a_{ii-1} & a_{1i}/a_{ii} & a_{1i+1} - a_{1i}a_{ii+1} & \cdots & a_{1n} - a_{1i}a_{in} \\ \vdots & \ddots & & & & \cdot^{\cdot^{\cdot}} & \vdots \\ \vdots & & \ddots & \dfrac{a_{i-1i}}{a_{ii}} & \cdot^{\cdot^{\cdot}} & & \vdots \\ -\dfrac{a_{i1}}{a_{ii}} & \cdots & -\dfrac{a_{ii-1}}{a_{ii}} & \dfrac{1}{a_{ii}} & -\dfrac{a_{ii+1}}{a_{ii}} & \cdots & -\dfrac{a_{in}}{a_{ii}} \\ \vdots & & \cdot^{\cdot^{\cdot}} & \dfrac{a_{i+1i}}{a_{ii}} & \ddots & & \vdots \\ \vdots & \cdot^{\cdot^{\cdot}} & & & & \ddots & \vdots \\ a_{n1} - a_{ni}a_{i1} & \cdots & a_{ni-1} - a_{ni}a_{ii-1} & \dfrac{a_{ni}}{a_{ii}} & a_{ni+1} - a_{ni}a_{ii+1} & \cdots & a_{nn} - a_{ni}a_{in} \end{bmatrix} \tag{7}$$

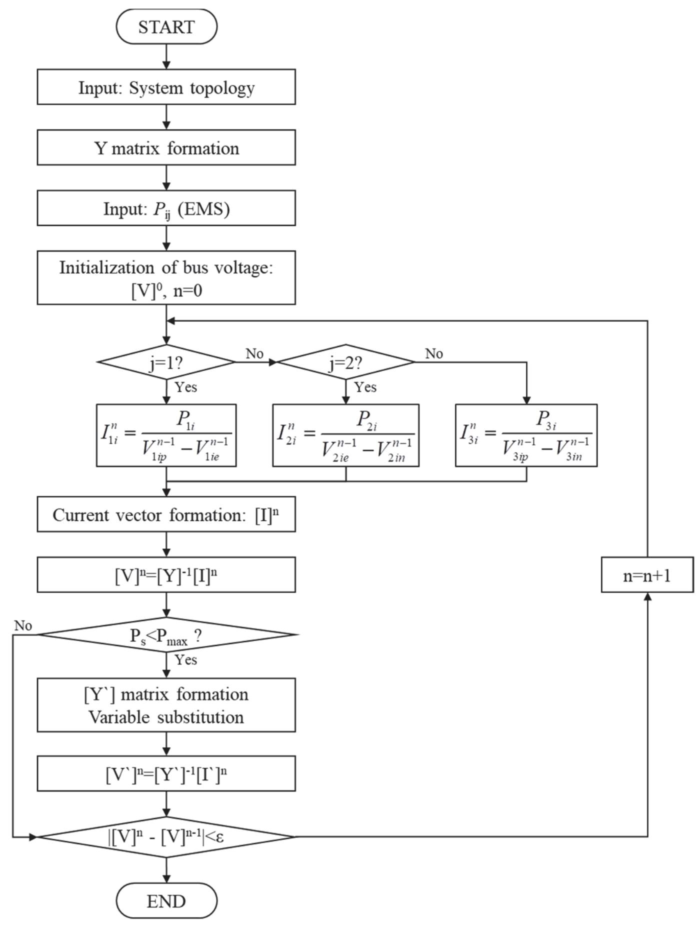

Fig. 7. Flowchart of the power flow calculation algorithm for a bipolar DC distribution system.

maintains its maximum in a range exceeding the rating.

The most discernible functional feature of DC distribution network compared with ordinary AC distribution network is that it allows the flexible control of the supply voltage depending on load or output of generating elements. Fig. 6 shows the simple pattern of operating voltage of converter terminals when the load demand is high 1.05 [pu] and when the output of generation elements at the end of the lines is high 0.95 [pu] compared with the operating condition with output voltage of 1.0 [pu]. The current limit of the normal operation by switching components lead to the breaking point of the operating voltage.

Control of V_{dc} means that the equivalent current in Eq. (1) changes, and the elements in row 1 and 2 which are converter current in current vector on the right side of Eq. (2) are converted to variables, not constants, and V_{po} and V_{ne} in row 1 and 2 which are converter terminal voltage in voltage vector on the left are converted to constants, not variables. The circuit equation in Eq. (2) is re-arranged with variable and constant vectors as shown in Eq. (6) by changing locations of the elements in row 1 and row 2, and the conductance matrix (Y) is derived as a new relation equation with the changing process of Eq. (7). Equation (7) shows the general form of relation matrix conversion when changing the location of elements in i-th row.

Power flow calculation for a bipolar converter-based DC distribution network can be performed through the processes described above and Fig. 7 shows a flowchart of the whole algorithm. The process of bus voltage initialization in Fig. 7 is a process of setting the initial voltage value to a no-load state with 750 [V] for the positive pole bus, 0 [V] for the neutral line bus and -750 [V] for the negative pole bus, with the assumption of ±750 [V] system. From the initially set voltage, voltage difference between two points and the current value of the initial load or generation elements from the power values before the measurement are calculated depending on the connection of the load and an updated bus voltage set is calculated by solving the circuit equations and the current values are updated again. These processes are repeated until the voltage vector of the previous step and the geometric distances are reduced below the certain values. In this method of power flow calculation, the equivalent AC/DC converter can be modeled as voltage and current

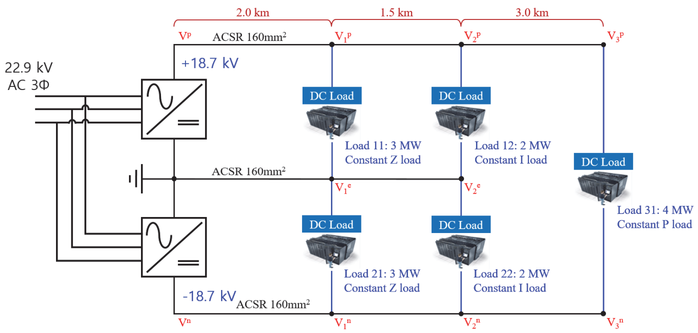

Fig. 8. Balanced bipolar DC distribution system and load conditions.

TABLE 2
Numerical Changes for the Entire Iterative Calculation Process for Balanced DC System

		Step 0	Step 1	Step 2	Step 3
Voltage (kV)	ps	18.700	18.689	18.689	18.689
	ns	-18.700	-18.689	-18.689	-18.689
	p1	18.700	18.619	18.619	18.619
	p2	18.700	18.589	18.588	18.588
	p3	18.700	18.558	18.558	18.558
	n1	-18.700	-18.619	-18.619	-18.619
	n2	-18.700	-18.589	-18.588	-18.588
	n3	-18.700	-18.558	-18.558	-18.558
	e1	0.000	0.000	0.000	0.000
	e2	0.000	0.000	0.000	0.000
Load (MW)	L11	3.000	2.974	2.974	
	L12	2.000	1.988	1.988	
	L21	3.000	2.974	2.974	
	L22	2.000	1.988	1.988	
	L31	4.000	4.000	4.000	
Load current (A)	L11	160.428	159.730	159.730	
	L12	106.952	106.952	106.952	
	L21	160.428	159.730	159.730	
	L22	106.952	106.952	106.952	
	L31	106.952	107.768	107.770	
Node Current Injection (A)	ps	632611.64	632611.64	632611.64	
	ns	-632611.64	-632611.64	-632611.64	
	p1	-160.43	-159.73	-159.73	
	p2	-106.95	-106.95	-106.95	
	p3	-106.95	-107.77	-107.77	
	n1	160.43	159.73	159.73	
	n2	106.95	106.95	106.95	
	n3	106.95	107.77	107.77	
	e1	0.00	0.00	0.00	
	e2	0.00	0.00	0.00	
Mismatch			0.316	4.9372E-06	4.4033E-11

sources, making the analysis easy, it can also be modeled as variable voltage source with variable voltage capability, and the constant voltage mode can be cleared when current exceeding the rating is supplied. Also, comprehensive analysis of elements connected between the positive pole and neutral line, the negative pole and neutral line, and between the positive pole and negative pole, and analysis of neutral line voltage through neutral line current analysis, are all possible, and analysis considering load unbalance between the poles is possible as well. Finally, this method of power flow calculation can resolve any difficulties in configuring the Jacobian matrix due to two slacks, and can reduce the computing load needed for deriving the result of power flow calculation by utilizing power flow analysis based on a Y matrix.

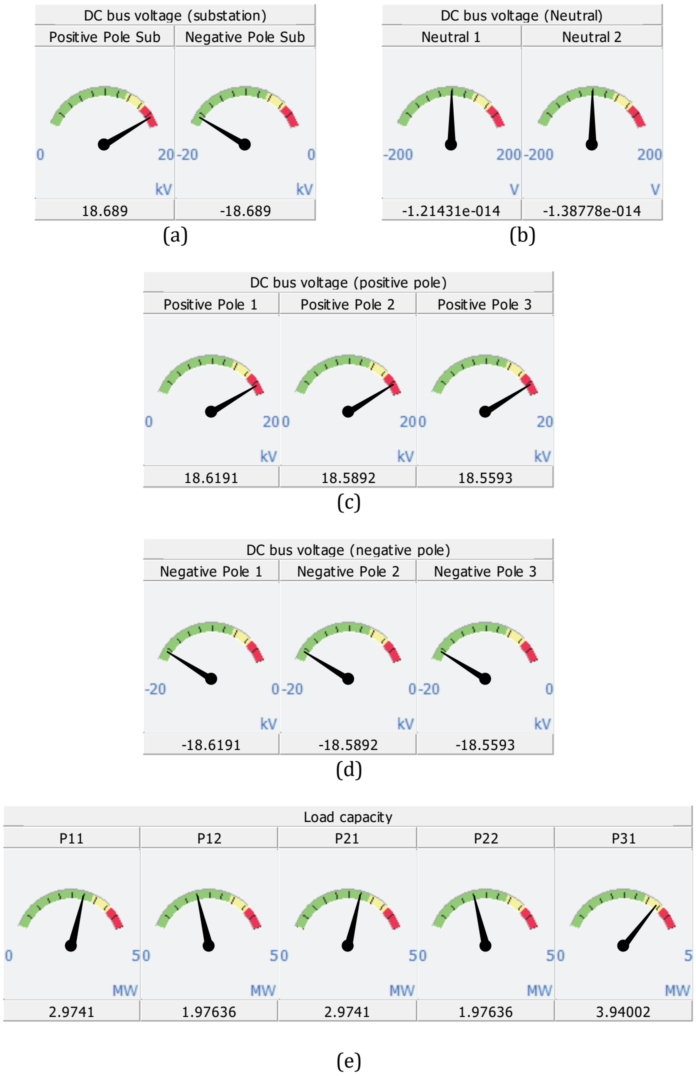

Fig. 9. Balanced bipolar DC distribution system and load conditions. (a) substation bus voltage. (b) neutral line bus voltage. (c) positive pole bus voltage. (d) negative pole bus voltage. (e) negative pole bus voltage

B. Simulation of Proposed Power Flow Calculation Method

In order to verify the validity of the proposed power flow algorithm, power flow analysis for balanced and unbalanced bipolar DC distribution network has been performed. The analysis results are compared with the electric circuit analysis results of the commercial tool for electromagnetic transient simulation, PSCAD/EMTDC which does not include power flow analysis function

1) Balanced Load Scenario

As shown in Fig. 8, balanced bipolar DC distribution system which includes 5 loads is assumed and power flow analysis for it has been performed. There are same type and capacity loads for each pole-to-neutral for balanced bipolar system. TABLE 2 shows the numerical changes for each variable during iterative process. For the lower mismatch than 1.0e-10, the strong convergence of the proposed algorithm can be confirmed in that the solution can be obtained with only 3 iteration steps. Comparing TABLE 2 from proposed algorithm and Fig. 9 from PSCAD/EMTDC, it can be seen that there are only a few volts of calculation difference. In Fig. 9(e),

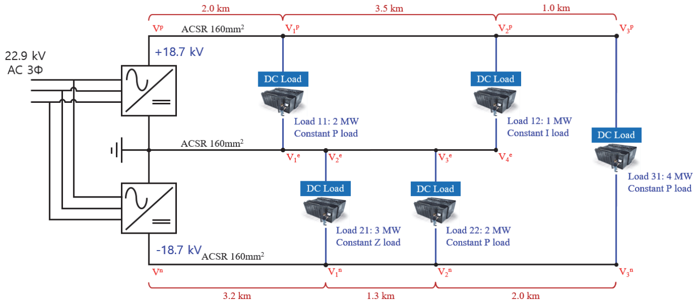

Fig. 10. Unbalanced bipolar DC distribution system and load conditions.

TABLE 3
Numerical Changes for the Entire Iterative Calculation Process for Unbalanced DC System

			Step 0	Step 1	Step 2	Step 3	Step 4
Voltage	(kV)	ps	18.700	18.684	18.684	18.684	18.684
		ns	-18.700	-18.683	-18.683	-18.683	-18.683
		p1	18.700	18.584	18.583	18.583	18.583
		p2	18.700	18.478	18.476	18.476	18.476
		p3	18.700	18.458	18.456	18.456	18.456
		n1	-18.700	-18.506	-18.506	-18.506	-18.506
		n2	-18.700	-18.454	-18.453	-18.453	-18.453
		n3	-18.700	-18.413	-18.412	-18.412	-18.412
	(V)	e1	0.000	-10.043	-9.436	-9.433	-9.433
		e2	0.000	-40.171	-39.338	-39.336	-39.336
		e3	0.000	-53.227	-52.393	-52.391	-52.391
		e4	0.000	-43.184	-42.351	-42.348	-42.348
Load (MW)		L11	4.000	4.000	4.000	4.000	
		L12	2.000	1.981	1.981	1.981	
		L21	3.000	2.925	2.925	2.925	
		L22	4.000	3.936	3.936	3.936	
		L31	8.000	8.000	8.000	8.000	
Load current (A)		L11	213.904	215.125	215.143	215.143	
		L12	106.952	106.952	106.952	106.952	
		L21	160.428	158.418	158.422	158.422	
		L22	213.904	213.904	213.904	213.904	
		L31	213.904	216.969	216.989	216.990	
Node Current Injection (A)		ps	632611.64	632611.64	632611.64	632611.64	
		ns	-632611.64	-632611.64	-632611.64	-632611.64	
		p1	-213.90	-215.13	-215.14	-215.14	
		p2	-106.95	-106.95	-106.95	-106.95	
		p3	-213.90	-216.97	-216.99	-216.99	
		n1	160.43	158.42	158.42	158.42	
		n2	213.90	213.90	213.90	213.90	
		n3	213.90	216.97	216.99	216.99	
		e1	213.90	215.13	215.14	215.14	
		e2	-160.43	-158.42	-158.42	-158.42	
		e3	-213.90	-213.90	-213.90	-213.90	
		e4	106.95	106.95	106.95	106.95	
Mismatch				14.383	0.0010142	6.605E-08	4.61003E-12

considering that the magnitude of the constant power load, P31, is calculated to be less than 4 MW, the low accuracy of the line-to-line constant power load model might be a cause of this calculation error.

2) Unbalanced Load Scenario

Power flow analysis for unbalanced bipolar DC distribution system as shown in Fig. 10 has been performed. There are different types and capacity of loads for each pole-to-neutral. TABLE 3 still shows the strong convergence of the proposed algorithm in that the solution can be obtained with only 4 iteration steps. Comparing TABLE 3 and Fig. 11, the high accuracy of the proposed algorithm can be verified in that there are only a few volts of calculation difference.

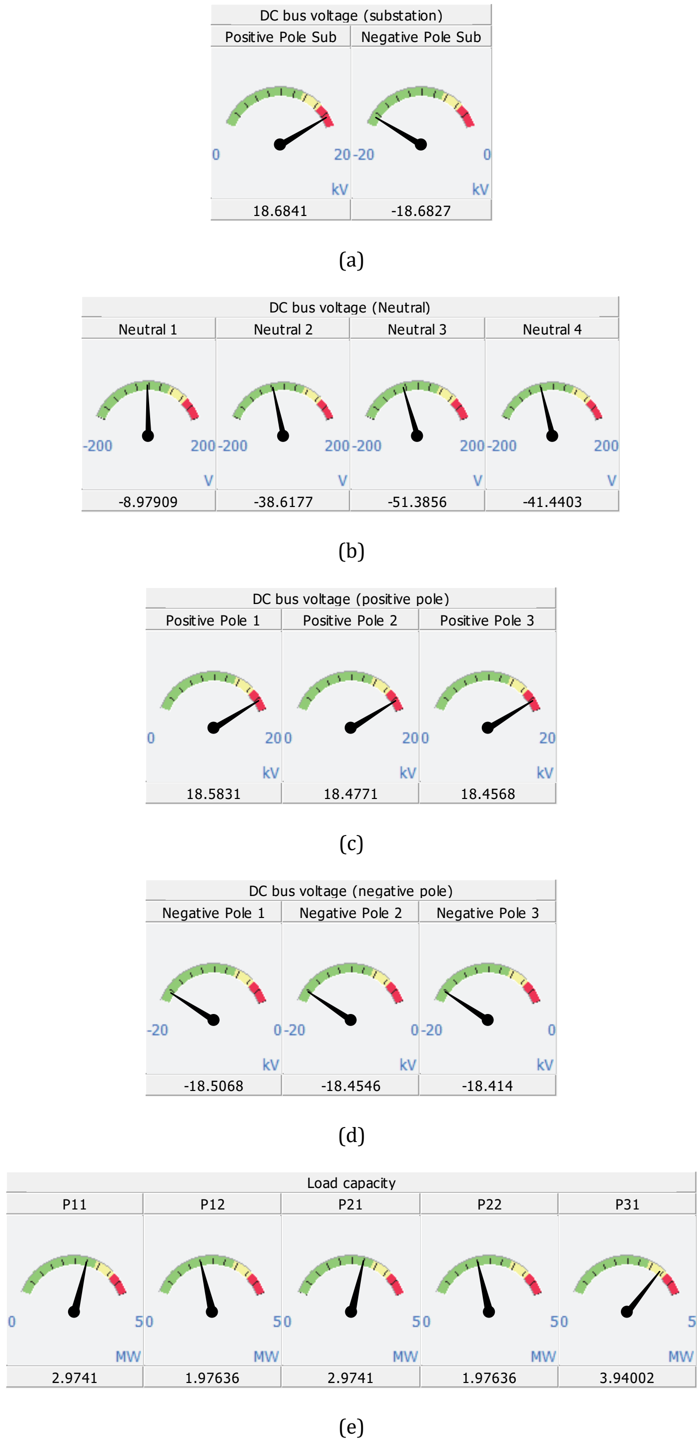

Fig 11. EMTDC simulation results for unbalanced DC system. (a) substation bus voltage. (b) neutral line bus voltage. (c) positive pole bus voltage. (d) negative pole bus voltage. (e) negative pole bus voltage.

IV. Conclusion

With rapid increase of large-scale DC load, renewable energy and distributed generation, research and development on DC distribution network have been globally performed. The DC distribution system has to achieve a cost-effective operation with the accurate simple analysis method. In addition, the analysis method for the application of an DC distribution system needs improved processing speed. In this paper, methods of power flow calculation for DC distribution network with bipolar structure have been proposed and the accuracy and simplicity have been verified by comparing with analysis and PSCAD/EMTDC simulation results. In the future, it will be necessary for DC distribution operation system to develop the proposed power flow calculation application and to apply for the actual power network system.

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