DC Distribution System to Enhance RES based DG Penetration through Converter Voltage Control

Bokyung Ko, Sungyoon Song, Yeuntae Yoon, Gilsoo Jang

***Abstract*-- As grid-integrated renewable energy sources (RES) are more prevalently connected to low-voltage grid, studies for impacts of these have attracted attention from system operators. Although the RESs are environmentally-friendly, the high penetration of RES based distributed generation (DG) in distribution system can cause an overvoltage problem due to a reverse power flow. To regulate the voltage in an AC system, an on load tap changer and reactive power control can be applied. However, these methods to regulate voltage are not suitable when operating the system with varying RES output. For the purpose of enhancing the RES based DG penetration, this research proposes a novel algorithm for a DC distribution system topology utilizing a DC current sensing based converter voltage control where a portion of the distribution system is converted to the DC form to actively correct the voltage and ensure that the control is independent of other distribution lines. In this paper, simulations use a novel algorithm to demonstrate the effect of DC distribution on voltage regulation.**

***Keywords*: Distribution system, DC distribution, voltage regulation, photovoltaic (PV), distributed generation (DG), overvoltage, converter voltage control**

I. Introduction

To reduce greenhouse gas emissions, various types of renewable energy generation has been developed. Although most of the renewable energy generations are susceptible to natural environments and highly environment-dependent, these energy resources do play an important role in energy plan. As many countries promote renewable energy generation, it is expected that more and more PV systems will be connected to power grid. With PV penetration in low voltage distribution system, the overvoltage issue in distribution system is highly concerned. During high generation of PV, there is a possibility of voltage-rise by reverse power flow and active power inflow. Owing to the voltage regulation constraint factor, the PV penetration amount in low voltage distribution system is often limited.

In the Korea Electric Power Corporation's (KEPCO) system, the PV concentrated areas in the low voltage distribution systems, such as the Cheon-an distribution system, generally experience over-voltage problems. This suburb has 36 houses. Each house has a 2.5kW PV panel on one phase (A phase). During high insolation, excessive power from the PV system can occur at each branch and this reverse power flow causes the voltage to increase [1]-[4]. This reverse power flow causes voltage rise. As shown in Fig. 1, the voltage on A phase in this KEPCO distribution system experiences a higher voltage than the other phases during the period of high PV generation. As KEPCO operating voltage range is restricted to 220V±13V, the PV penetration can be limited by voltage regulation problem.

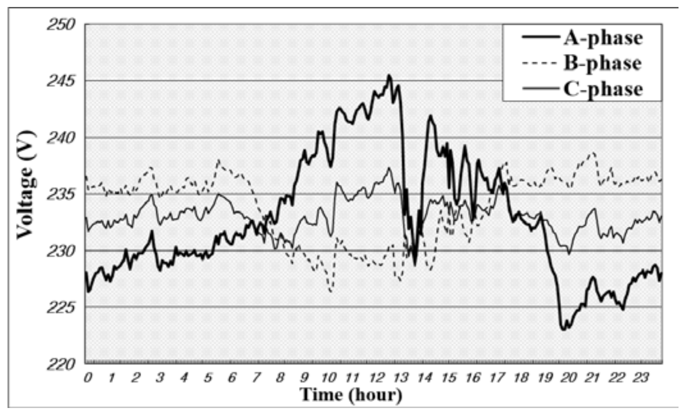

Fig. 1. Voltage profile with PV generations in KEPCO's low voltage distribution system (x-axis: hour, y-axis: V)

This paper proposes a DC distribution system voltage control strategy to alleviate the voltage rise problem in distribution system by controlling the voltage through a VSC-converter that considers the PV generation output. This control strategy is based on the correlation between generation and load which is main factor of voltage rise. Through PSCAD simulations, the effect of voltage control algorithm of VSC-converter to correct the distribution voltage is verified.

II. The Configuration of the PV Concentrated Area

A. *PV concentrated distribution system*

As shown in Fig. 2, the Cheon-an PV concentrated area, a distribution system in the KEPCO system comprises 36 houses that each have a PV panel. Each house and PV panel are connected with a 220V distribution line and six units are lumped into one connection point through one branch line. To configure the distribution system shown in Fig. 2 in Power

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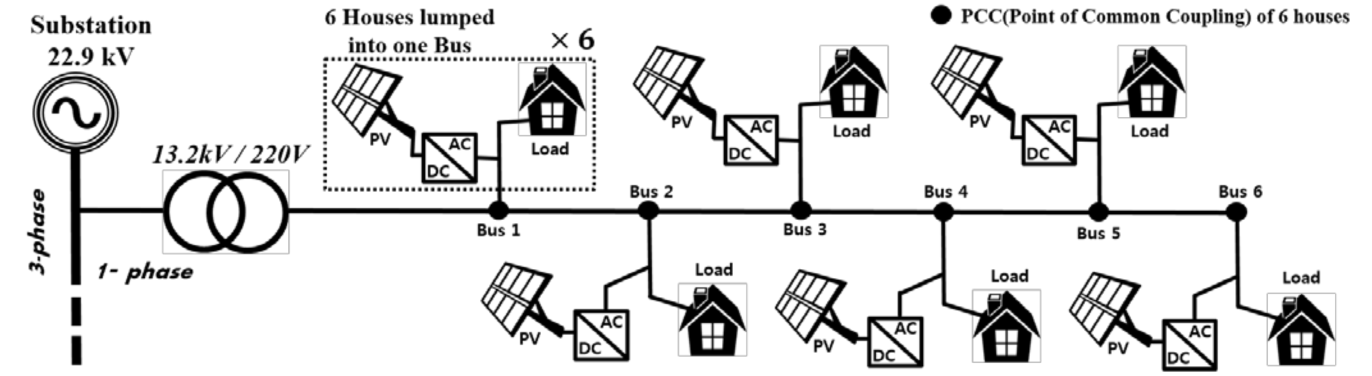

Fig. 2. Configuration of PV concentrated overhead AC distribution system in KEPCO

System Computer Aided Design (PSCAD), this paper referred to the Cheon-an distribution system data of KEPCO. Fig. 3 shows the power flow of one house including the PV generation of one day. The PV generation data is measured at the connection point of a house. In accordance of these data, around 1.85kW of surplus power from each house is produced at midday. This surplus power inflow has a significant impact on the overvoltage problem of the distribution system [5]-[6].

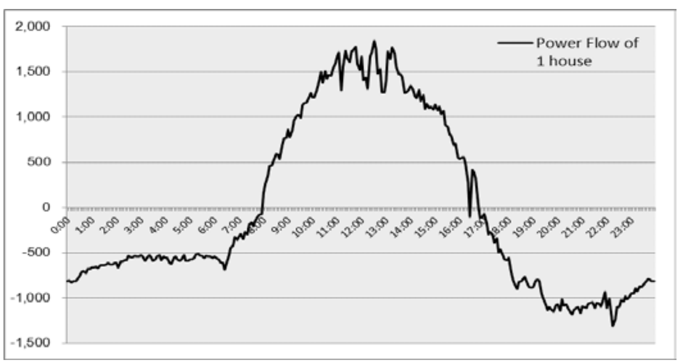

Fig. 3. Data on power generation output of 1 house with PV during one day (x-axis: hour, y-axis: Watt)

The degree of voltage rise mainly depends on the amount of current flow and impedance of distribution lines. The larger line impedance is, the greater voltage rise happens line impedance is, the greater voltage rise happens. This paper applied the OW-60mm line data shown in TABLE I.

TABLE I
SINGLE PHASE PI SECTION LINES PARAMETERS (PERE CONDUCTOR)

	R (Ω/km)	L (mH/km)	C (μF/km)
OW 60mm^2	0.313	0.266	0.0013

B. Benefit of DC Application on PV Concentrated Area

Owing to the high PV penetration, Cheon-an distribution site is a candidate for DC distribution implementation to enhance the PV penetration. The energy losses entailed in converting DC to AC could be eliminated in DC distribution system. And additional main reasons to apply an DC system is that it is promising solution to meet future power system requirements, including integrated energy management on RES power plant [7], [8]. This integrated management concept is on controlling the distributed generation as one integrated unit, not an individual resource. Because of these reason, DC distribution system application is considered in Cheon-an area and this paper deals with the control algorithm of DC distribution system.

C. DC Application on PV Concentrated Distribution System

DC distribution system is a new innovation in the field of distribution power systems, which comprise power electronic converters and a DC link as shown in Fig. 4. AC/DC conversion is conducted near the 13.2kV/220V transformer. This paper proposed a unipolar system that has one voltage level. Although the unipolar system has lower transmission capacity, the cost is considerably reduced because of the decrease in the number of power electronic devices used and the total load/generation being under 100kVA in the simulated distribution system. Therefore, the simulation is performed using an unipolar DC distribution system.

III. SIMULATION METHODOLOGY FOR DC SYSTEM

A. Power Flow Calculation for a DC Line Voltage Analysis

To verify the proposed DC current sensing based converter voltage control algorithm in PSCAD/EMTDC simulation, the mathematical analysis on the line voltage of a DC distribution system is conducted using a power-flow calculation. By analyzing the interrelation between the injected power flow and line voltage at each bus mathematically, the parameters for the voltage control of the feeder-header converter are computed. Although the proposed DC power flow equation is induced from the AC power flow equation expressed in (1) and (2), it requires some assumptions reflecting the DC power flow characteristic. The basic two assumptions for the DC power flow calculation are explained below.

$$P_k = V_k \sum_{i=1}^{N} V_i [G_{ki} \cos(\theta_k - \theta_i) + B_{ki} \sin(\theta_k - \theta_i)] \quad (1)$$

$$Q_k = V_k \sum_{i=1}^{N} V_i [G_{ki} \sin(\theta_k - \theta_i) - B_{ki} \cos(\theta_k - \theta_i)] \quad (2)$$

- No reactive power transfer through the DC distribution line: Q_k equation can be excluded
- The phase difference between the DC line voltage and the current is zero

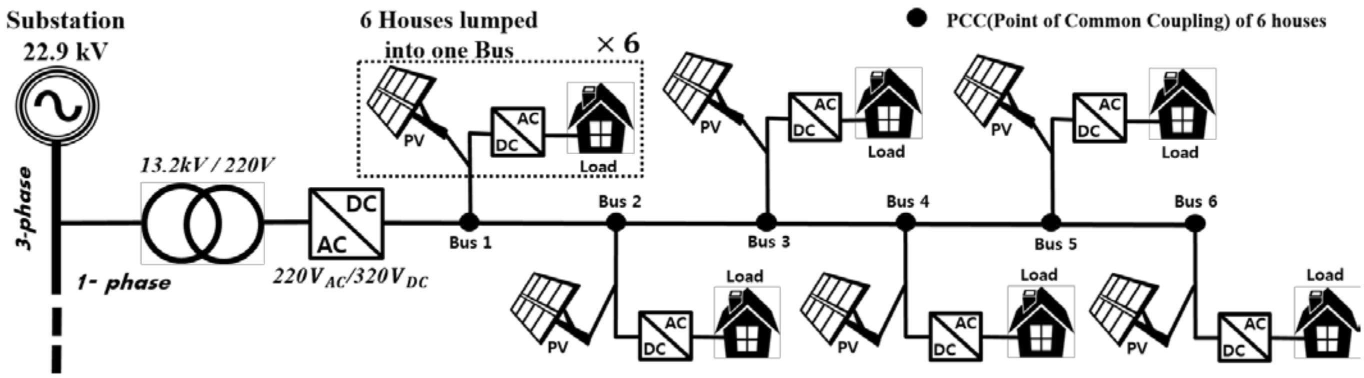

Fig. 4. Configuration of the proposed PV concentrated overhead DC distribution system

Based on these two assumption, the DC power flow equation can be modified as shown in (3). To induce the formulation regarding the correlation between the variance of the power injection and the voltage at each bus, partial differentiation is applied in (3). The correlation equation can be derived as in (4).

$$P_k = V_k \sum_{i=1}^{N} V_i [G_{ki}] \tag{3}$$

$$\Delta P_i = \sum_{k=1}^{N} \frac{\partial P_i}{\partial V_k} \Delta V_k \tag{4}$$

Based on Equation (4), active power-voltage correlation matrix (5) is induced and the voltage variation at each converter station is estimated. Equation (5) explains the correlation between active power injection and voltage at each converter station. Based on the measured DC current at master converter, the degree of a voltage variation is estimated. If the distribution line voltage deviates from the permissible range, the proposed algorithm calculates the required amount of a voltage compensation for stabilizing the voltage.

$$\begin{bmatrix} \frac{\Delta V_1}{V_1} \\ \frac{\Delta V_2}{V_2} \\ \frac{\Delta V_3}{V_3} \\ \vdots \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\left(\frac{\partial V_1}{V_1}\right)} & \frac{\partial P_1}{\left(\frac{\partial V_2}{V_2}\right)} & \frac{\partial P_1}{\left(\frac{\partial V_3}{V_3}\right)} & \cdots \\ \frac{\partial P_2}{\left(\frac{\partial V_1}{V_1}\right)} & \frac{\partial P_2}{\left(\frac{\partial V_2}{V_2}\right)} & \frac{\partial P_2}{\left(\frac{\partial V_3}{V_3}\right)} & \cdots \\ \frac{\partial P_3}{\left(\frac{\partial V_1}{V_1}\right)} & \frac{\partial P_3}{\left(\frac{\partial V_2}{V_2}\right)} & \frac{\partial P_3}{\left(\frac{\partial V_3}{V_3}\right)} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \\ \vdots \end{bmatrix} \tag{5}$$

$$\frac{\partial P_i}{\left(\frac{\partial V_k}{V_k}\right)} = V_i V_k G_{ik} \tag{6}$$

IV. Simulation Configuration

Since PVs produce excessive power at midday, large reverse power flow causes overvoltage problems. As shown in Fig. 5, if the PVs are connected at the lower part of the distribution system, the voltage variation during high insolation period increases more. Equation (7) and (8) show the interrelation of the voltage variation and power inflow, as well as line impedance. In addition, it can be concluded that the lower part of the distribution line is vulnerable to overvoltage problem caused by PV generation output.

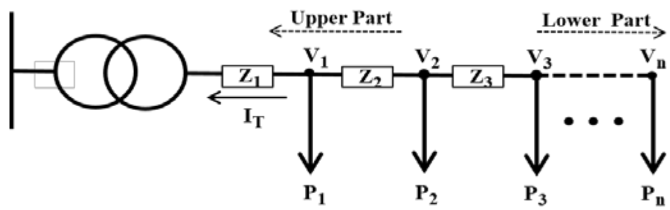

Fig. 5. Configuration of distribution power flow

$$\Delta V_n = Z_1 \sum_{k=1}^{n} \frac{P_k}{V_k} + Z_2 \sum_{k=2}^{n} \frac{P_k}{V_k} + \cdots + Z_n \frac{P_n}{V_n} \tag{7}$$

$$= \frac{P_1}{V_1} Z_1 + \frac{P_2}{V_2} \sum_{k=1}^{2} Z_k + \cdots + \frac{P_n}{V_n} \sum_{k=1}^{n} Z_k \tag{8}$$

A. Existing AC Distribution System

The voltage variation of AC distribution system depending on the PV generation output is simulated by PSCAD/EMTDC. Through the simulation, it is demonstrated how much the AC system voltage deviates from the permitted voltage variation range of KEPCO system shown in Table II.

TABLE II
Permissible Voltage Variation Range of KEPCO System

Nominal Voltage	Permitted Range	% Variation
110	104 ~ 106	6 %
220	207 ~ 233	6 %
380	342 ~ 418	10 %
440	414 ~ 466	6 %

As shown in Fig. 6, some of buses in AC distribution line, bus 3 through 6, experience the overvoltage problem during high PV generation period. From the simulation result, it is demonstrated that the lower part (near to Bus 6) of the distribution line is more vulnerable to overvoltage problem, causing from PV generation, than the upper part (near Bus1). Maximum voltage at bus 6 can reach up to 241.9V during a day. Since the voltage variation at bus 6 exceeds the permitted limit of 233V by 8.9V, additional actions for voltage stabilization such as restriction on PV penetration is required. In this paper, the voltage regulation function by utilizing the VSC-converter in DC distribution system is proposed to make distribution line voltage operate within stable range.

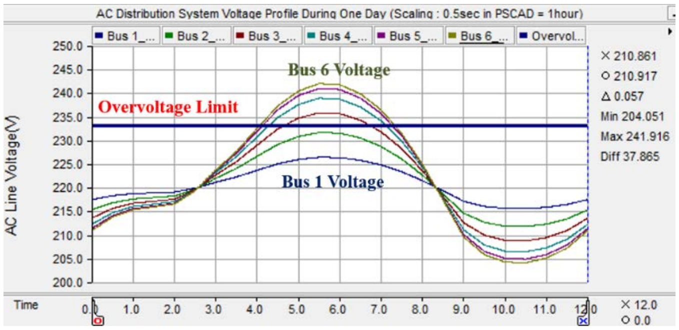

Fig. 6. AC distribution line voltage at upper part (Bus1) ~ lower part (Bus6)

B. Proposed DC Distribution System

This paper proposes a DC distribution system, which consists of power electronic converters to enhance PV penetration by utilizing the voltage controllability of the VSC. In the KEPCO power system, 320VDC, which is close to the peak to peak value of a RMS 220VAC standard voltage, is considered as the standard voltage level for the DC distribution systems. Therefore, this paper assumes that the DC voltage level is 320VDC and the permissible voltage variation range is strictly assumed as ± 13V, which is the same as the variation limit in AC system.

Fig. 7 presents the voltage profile of the DC distribution system. The DC distribution system also experiences the overvoltage problem during high PV power injection. However, owing to the lower impedance characteristics in DC environment and the higher standard voltage, the amount of voltage rise in the DC system is lower than in the AC. To verify the effect of the proposed converter control algorithm on enhancing the PV penetration, the performance of the algorithm will be tested with increasing PV penetration ratio.

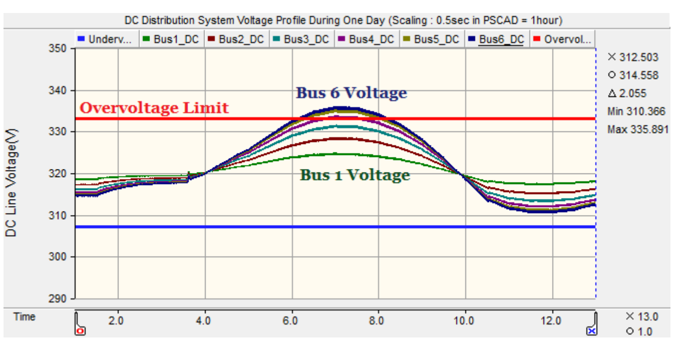

Fig. 7. DC distribution line voltage at upper part (Bus1) ~ lower part (Bus6)

C. Voltage Compensation through Converter Control

To independently control the voltage of a distribution line that is connected to PVs, a DC distribution topology is proposed where the corresponding distribution system's voltage can be regulated through the active VSC control. In this paper, to control the varying voltage resulting from the fluctuating PV generation output, a voltage control algorithm for the VSC is proposed. The proposed DC line voltage control method can be accomplished by simply controlling the electrical input signal, i.e. by adjusting the DC voltage reference on the voltage controller of a VSC according to the interrelation of the load and PV generation. The proposed algorithm is based on the DC current, measured near the converter station. Based on the measured DC current, the degree of a voltage variation is estimated. If the distribution line voltage deviates from the permissible range, the proposed algorithm calculates the required amount of a voltage compensation for stabilizing the voltage. This calculated value is added to DC voltage reference. This modified reference that reflects the amount of PV generation is an input of the voltage controller as shown in Fig.8.

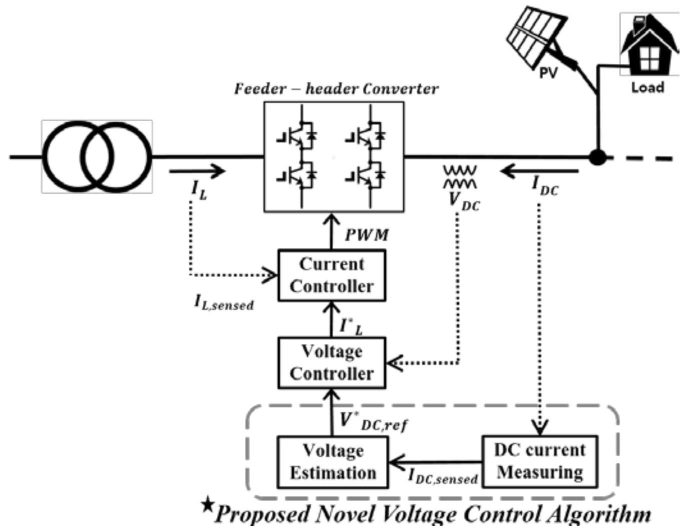

Fig. 8. Control blocks of proposed novel voltage control algorithm

V. Simulation Result

In order to verify the voltage compensation performance of a proposed algorithm, PSCAD simulation is performed in a real KEPCO distribution system. The simulation process verifies the benefit of the proposed voltage control algorithm on enhancing the PV penetration. By implementing the proposed DC voltage reference compensating algorithm on the VSC voltage controller, the distribution system voltage can be regulated within the voltage variation limit. By comparing Fig. 7 and 9, we can observe that the overvoltage problem is effectively compensated. When an overvoltage state occurs, which can be estimated from a measured current (I_{DC}), the value of the compensating voltage become non-zero value and compensation voltage modifies the DC voltage reference (V_{DC_ref}) on voltage controller.

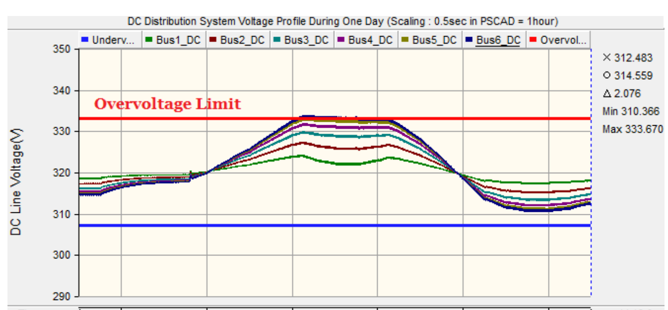

Fig. 9. Compensated DC voltage profile for each bus over one day
(Each PV capacity = 2.5kW)

Fig. 10 shows the variation aspect of the DC voltage reference on VSC voltage controller. When an overvoltage problem happens during midday, the DC voltage reference decreases to lower the whole distribution line voltage.

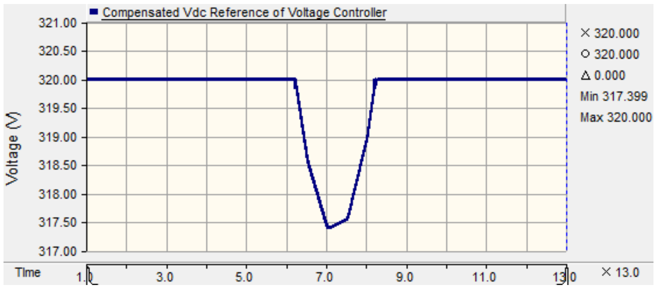

Fig. 10. Variation aspect of the DC voltage reference on voltage controller (Each PV capacity = 2.5kW)

In order to verify the performance relevant to PV penetration enhancement, the proposed algorithm is demonstrated with increasing PV capacity. When PV generation at each house exceeds 3.6kW, the compensated DC voltage reference reaches the low voltage limit of distribution line (307V). Therefore, this capacity of PV penetration can be a limit for the proposed DC topology. Without the proposed algorithm, when the distribution line is connected to each 3.6kW PV, the line voltage reaches up to 345V as shown in Fig. 11. However, if the proposed DC voltage compensation algorithm is applied to voltage controller of VSC, the line voltage can maintain stable condition up to 3.6kW PV penetration without causing any violation of the distribution system voltage limit. Fig. 12 shows this result and this result demonstrated that the ratio of PV penetration can effectively increase through the proposed DC voltage regulation algorithm.

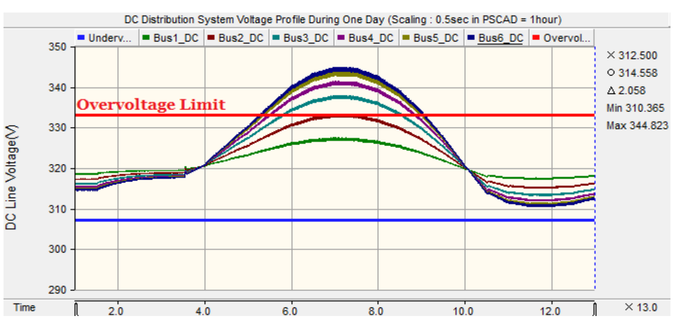

Fig. 11. DC voltage profile without the proposed algorithm (Each PV capacity= 3.6kW)

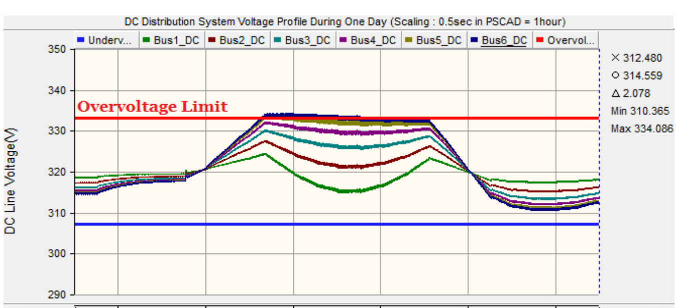

Fig. 12. Compensated DC voltage profile at each bus (Each PV capacity=3.6kW)

VI. Conclusions

This paper presents the effect of a novel DC distribution system topology on enhancement of PV penetration. Through simulations by applying the VSC-converter's voltage control algorithm, it is shown that voltage corrective action of converter in DC system is properly conducted. A KEPCO (Korea Electric Power Corporation) distribution system is selected for simulation to verify the performance of a proposed algorithm. The proposed algorithm is demonstrated that it is properly operating with respect to daily repeated voltage fluctuation according a PV generation. The compensation algorithm is based on a DC distribution line current which reflects a loading condition. According to the magnitude and sign of DC line current, the rate and direction of compensation is determined. Through PSCAD simulations, it is verified that a compensation operation is properly conducted with respect to a daily repeated fluctuating PV generation which restricts a PV penetration on distribution line.

VII. Acknowledgment

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