研究論文

D-UPFC Voltage Control in the Bi-directional Power Flow Condition

Kyungsoo LEE [*1] Kenichiro YAMAGUCHI[*1] Kosuke KUROKAWA [*1]

Abstract

This paper proposes distribution voltage control using distribution-unified power flow controller (D-UPFC) during forward power flow and reverse power flow condition. During forward power flow condition, voltage sags, swells, under- and over-voltage occur due to fault occuring or load conditions. In the reverse power flow condition, voltage increase happens because of reverse power flow from clustered PV system. D-UPFC consists of a transformer and bi-directional ac-ac converter. The transformer maintains a part of reference voltage and bi-directional ac-ac converter regulates the voltage to keep the reference voltage. Bi-directional ac-ac converter provides direct ac to ac conversion without storing energy. Also, distribution system model is used in order to analyze distribution voltage patterns and to verify the D-UPFC voltage control. Simulation results using ATP-EMTP program show the voltage control in the power flow and reverse power flow condition.

Key Words : Forward power flow, Reverse power flow, D-UPFC, Bi-directional ac-ac converter, ATP-EMTP

1. Introduction

In the power flow condition, faults occuring in power distribution systems or facilities in plants generally cause the voltage sags or swells. Also, power systems supply power for a wide variety of different user applications, and sensitivity to voltage sags and swells varies widely for different applications [1].

A few voltage control methods have been developed. Static var compensator (SVC) regulates over- and under-voltage conditions by controlling its reactive power. Autotransformer with line drop compensator based step voltage regulator (SVR) selects suitable voltage using a switch during voltage change. Also, scheduled operation controls distribution line voltage in the substation [2].

These voltge control methods concerns during forward power flow condition. Also, they are performed not the low-voltage distribution system but the high-voltage distribution system.

Reverse power flow happens when clustered PV system connects with distribution system. Voltage increase phenomenon happens due to reverse power flow. When the voltage increase occurs in the low-voltage distribution system, it affects to stop generating power from clustered PV system or to trouble distribution system equipments.

D-UPFC is proposed in the bi-directional power flow condition. It can fast control distribution voltage during voltage decrease as well as voltage increase condition. D-UPFC consists of a transformer and bi-directional ac-ac converter. The transformer maintains a part of reference voltage and bi-directional ac-ac converter regulates the voltage to keep the reference voltage during voltage decrease and increase condition.

This paper begins by studying D-UPFC analysis. D-UPFC voltage control concept is explained. Bi-directional ac-ac converter shows the voltage decrease and increase control methods, switching patterns. The transformer and bi-directional ac-ac converter capacity calculation is performed. Using the distribution model, voltage patterns are shown. Finally, ATP-EMTP simulation tool is employed in the D-UPFC voltage control.

2. D-UPFC analysis

2.1 D-UPFC voltage control concept

D-UPFC is proposed in order to control voltage decrease and increase phenomenon in the power flow and reverse power flow condition. The transformer and bi-directional ac-ac converter are the components of D-UPFC. Proposed D-UPFC topology uses

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transformer N_1' and N_2 but other reference papers uses N_1, N_2 and N_3 [3,4]. Proposed D-UPFC topology has the advantage of minimizing the transformer capacity. Proposed D-UPFC topology is shown in Fig. 1.

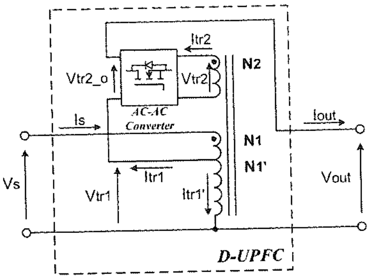
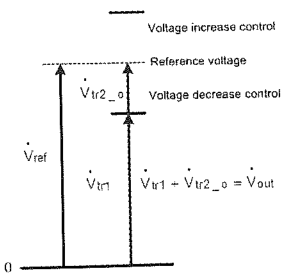


Fig. 1 Proposed D-UPFC topology.

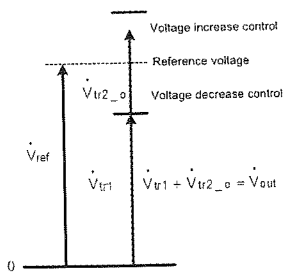
V_s is the distribution system side and V_{out} is load side. In the D-UPFC control, D-UPFC output voltage V_{out} is decided by V_{tr1} and V_{tr2_o}. The value of V_{tr1} is decided by the transformer voltage ratio N_1'. V_{tr2_o} is decided by bi-directional ac-ac converter and it controls voltage decrease and increase using pulse width modulation (PWM) control. In the normal distribution voltage condition, V_{tr2_o} keeps constant voltage by controlling the converter duty to 0.5. Thus, D-UPFC output voltage V_{out} is the same as reference voltage V_{ref}. If the voltage decrease happens, the ac-ac converter duty ratio increases over 0.5. Reversely, when the voltage increase occurs, the converter duty ratio decreases under 0.5. D-UPFC output voltage can be expressed,

$$\dot{V}_{out} = \dot{V}_{tr1} + \dot{V}_{tr2\_o} \tag{1}$$

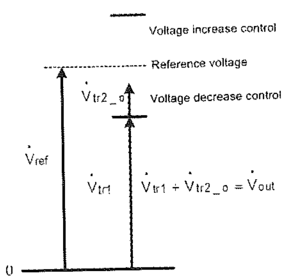
D-UPFC voltage control diagram is shown in Fig. 2.



(a) Normal state



(b) Voltage increase control



(c) Voltage decrease control

Fig. 2 D-UPFC voltage control diagram.

2. 2 Bi-directional ac-ac converter

Bi-directional ac-ac converter consists of four MOSFET switches, input and output filters. The converter is the step-down converter as the dc-dc buck-converter. The output voltage is always less than the input voltage and thus,

$$V_{tr2\_o} = V_{tr2} \times D \tag{2}$$

where, D is duty ratio of the bi-directional ac-ac converter

The converter provides direct ac to ac conversion, thus there is no energy storage device except input and output filters. The bi-directional ac-ac converter circuit is shown in Fig. 3.

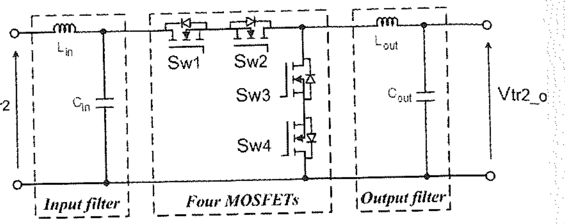


Fig. 3 Bi-directional ac-ac converter circuit.

The switching patterns of the converter offer safe commutation without high-voltage spikes using intelligent PWM switching patterns. Switching patterns are decided by the polarity of input voltage V_{tr2}. When V_{tr1} is positive, S_{w1} and S_{w3} act PWM switching, reversely. At the same time, S_{w2} and S_{w4} turn on state. If the sign of the V_{tr2} is changed, the switching patterns of four switches are reversed [5]. The converter switching diagram is shown in Fig. 4.

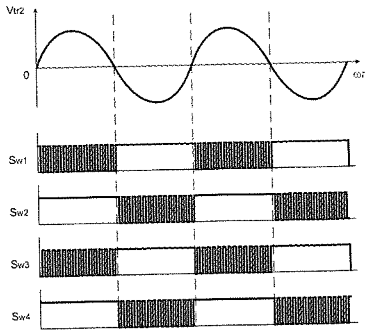


Fig. 4 Bi-directional ac-ac converter switching diagram.

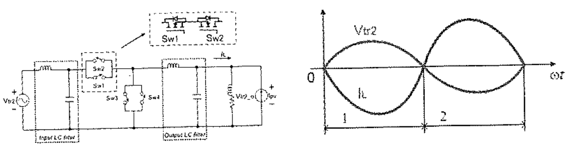
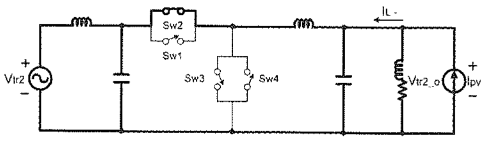


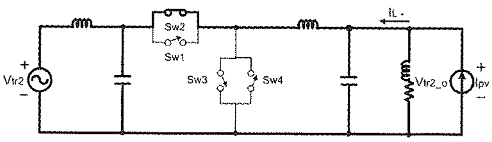
Fig. 5 Converter circuit and its input voltage, output current waveform.

Referenced paper shows the conveter switching patterns during power flow condition [3]. However, the reverse power flow switching patterns are necessary to control over-voltage phenomenon. The clustered PV system can be expressed as the current source and it connects with ac-ac converter. When the reverse power flows, the converter output current is reversed 180 degree. The converter circuit conneced with clustered PV system and its input voltage, output current are shown in Fig. 5.

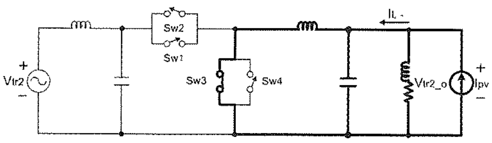
When the sign of V_{tr2} is positive and I_L is negative, Switch S_{w1} and S_{w3} perform PWM control, reversely. At the same time, S_{w3} and S_{w4} turn on state. At this state, three modes are generated as shown in referenced paper [5]. Active, dead-time and freewheeling modes are performed by the converter switching pattern. These three modes are shown in Fig. 6 (a) to (c). When the sign of V_{tr2} is changed, the reverse switching patterns are applied. Here, the reverse power flows to the distribution source but the load voltage V_{tr2_o} is always controlled.



(a) Active mode during V_{tr2} is positive



(b) Dead-time mode during V_{tr2} is positive



(c) Freewheeling mode during V_{tr2} is positive

Fig. 6 Reverse power flow switching patterns in the bi-directional ac-ac converter.

In the forward power flow condition, input voltage V_{tr2} and output current I_L relation of the converter is changed by load condition. In the resistive condition, the phase of input voltage and output current is the same. When the load is inductive condition, the output current lags θ the input voltage. In the capacitive load condition, the output current leads θ the input voltage. Also, the output current 2θ difference compared with input voltage in the reverse power flow condition. The phase diagram of the forward power flow, reverse power flow condition is shown in Fig. 7.

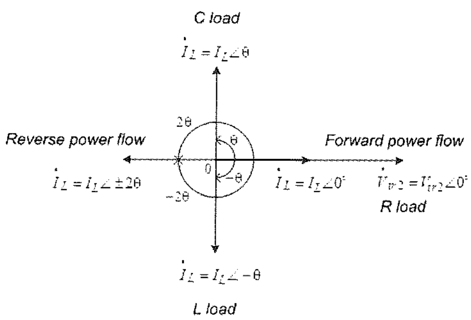


Fig. 7 Phase diagram of the converter input voltage and output current relation during bi-directional power flow condition.

2. 3 D-UPFC capacity calculation

As shown in Fig. 1, the D-UPFC capacity is decided by bi-directional ac-ac converter and the transformer. The low-voltage distribution system voltage range is 202 ± 20 (101 ± 6) [V,rms]. Considering from the converter capacity, the output voltage V_{tr2_o} compensates or regulates 20[V,rms] in this paper. Thus, D-UPFC can cover the distribution voltage until under- and over-voltage limit. In the normal condition, the converter operates with duty 0.5 and thus, the output voltage V_{tr2_o} of the converter is 20.2V[V,rms]. The input voltageV_{tr2} of the converter is 40.4[V,rms]. The transformer supported voltage V_{tr1} is 181.8[V,rms] because D-UPFC output voltage V_{out} should be 202[V,rms]. D-UPFC input voltage V_s is 202[V,rms]. Therefore, N_1, N_1' and N_2 are 1, 0.9 and 0.2, respectively.

The power relation between D-UPFC input and output is expressed,

$$P_s = V_s I_s \tag{3}$$

$$P_{tr1} = V_{tr1} I_{tr1} \tag{4}$$

$$P_{tr2} = V_{tr2} I_{tr2} \tag{5}$$

Transformer total power P_s is

$$P_s = P_{tr1} + P_{tr2} \tag{6}$$

$$V_s I_s = \frac{9}{10} V_{tr1} I_{tr1} + \frac{1}{5} V_{tr2} I_{tr2} \tag{7}$$

The bi-directional ac-ac converter input current I_{tr2} is decided by,

$$I_{tr2} = D I_{tr1} \tag{8}$$

Here, the converter duty D is 0.5 and thus,

$$V_s I_s = \frac{9}{10} V_{tr1} I_{tr1} + \frac{1}{10} V_{tr2} I_{tr1} \tag{9}$$

If the value of load is decided,

$$I_s = I_{tr1} = I_{out} \tag{10}$$

$$V_s I_s = \frac{9}{10} V_{tr1} I_s + \frac{1}{10} V_{tr2} I_s \tag{11}$$

2. 4 D-UPFC voltage control

In the D-UPFC voltage control, D-UPFC output voltage V_{out} is always controlled by refrence voltage V_{ref_dc}. V_{ref_dc} is the same as low-voltage distribution system voltage 202[V,rms] and it compares to V_{out}. V_{out} changes to root mean square (RMS) value. The error voltage V_{error} inputs PI compensator and then it adds reference duty V_{ref_duty}. V_{ref_duty} is 0.5. Finally, V_{pwm} compares to triangle waveform V_{tri} with 20[kHz] in the PWM control. D-UPFC voltage control block is shown in Fig. 8.

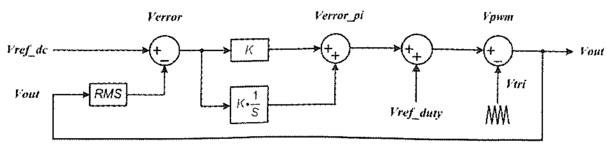
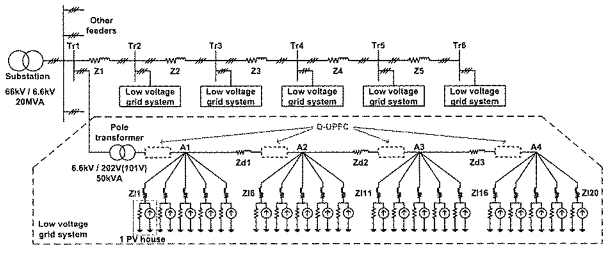


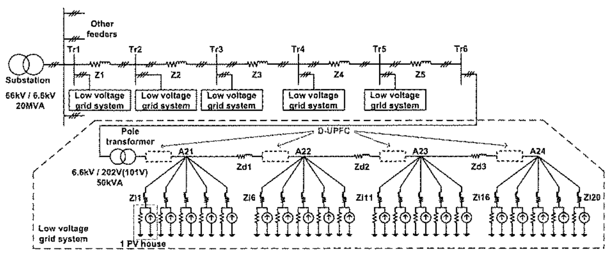
Fig. 8. D-UPFC voltage control block.

3. D-UPFC model

Distribution model is proposed in order to analyze distribution voltage characteristics according to load patterns. The second is to verify the D-UPFC voltage control when voltage decrease and increase happens in the bi-directional power flow condition. The distribution model using ATP-EMTP simulation program is shown in Fig. 9. This model is referenced from NEDO report [6]. It is assumed the residential area in Japan. The total feeder lines are eight. The length of one feeder is 10[km] and the low voltage grid system is located every 2[km]. Here, only one feeder line is scaled down and simulated. In the node A_1 to A_4 and node A_{21} to A_{24}, each 20 PV houses connects with the pole transformer. Node number A_1 to A_4 at 0[km] from substation is shown in Fig. 9 (a). Node number A_{21} to A_{24} at 10[km] from substation is shown in Fig. 9 (b). Detailed distribution model parameters are shown in table. 1.



(a) Node A_1 to A_4 of the distribution model



(b) Node A_{21} to A_{24} of the distribution model

Fig. 9 Distribution model.

Table 1 Distribution model parameters

Substation		66kV/6.6kV, 20MVA
Pole transformer		6.6kV/202V(101V), 50kVA
HV line impedance(Z_1 to Z_5)		0.626+j0.754[Ω/2km]
LV line impedance(Z_{d1} to Z_{d3})		0.025+j0.020[Ω/40m]
Lead-in wire imp.(Z_{i1} to Z_{i20})		0.0552+j0.037[Ω/20m]
Total load	Light load	4.08[Ω], 20% of pole trans.
	Heavy load	1.02[Ω], 80% of pole trans.
Each PV source		3[kW]

There are a few constaraints in the simulation:

(1) Each feeder is radial topology.

(2) Load is assumed to resistance.

(3) PV output power factor is 1.

D-UPFC parameters in the simulation are shown in Table 2. The input voltage V_s is 202[V,rms] and thus, the reference voltage V_{ref_dc} is the same as V_s. The switching frequency is 20[kHz]. In the Input and output filter design, input current and output voltage harmonics are should be removed [7].

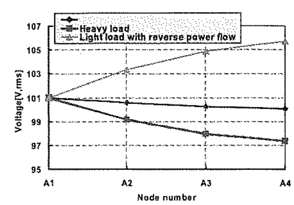
Table 2 D-UPFC parameters

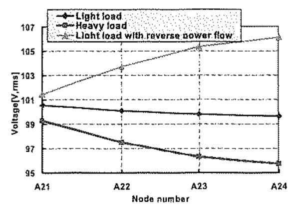
V_S	202[V,rms]	C_{in} & C_{out}	50[μF]
N_1: N_1': N_2	1:0.9:0.2	$V_{ref\ dc}$	202[V,rms]
V_{tr1}	181.8[V,rms]	PI gain	K_p=0.025 K_i=0.001
V_{tr2}	40.4[V,rms]	Switching freq.	20[kHz]
L_{in} & L_{out}	50[μH]	$V_{ref\ duty}$	0.5

4. Case study

4. 1 Voltage changes during load patterns

Light load and heavy load from forward power flow, reverse power flow conditions are simulated using distribution model. As mentioned earlier, the low-voltage distribution system voltage range is 202±20[V,rms]. In the simulation result, voltage range is shown in 101± 6[V,rms]. The simulation results due to load patterns from node A_1 to A_{24} are shown in Fig. 10. In the light load condition, total power of light load is 20[%] of pole transformer capacity. The low-voltage is decreased 101[V,rms] at node A_1 to 99.65[V,rms] at node A_{24}. In the heavy load condition, the load total power is 80[%] of pole transformer capacity. The low-voltage is decreased 101[V,rms] at node A_1 to 95.75[V,rms] at node A_{24}. The reverse power flow condition caused by clustered PV system is simulated.





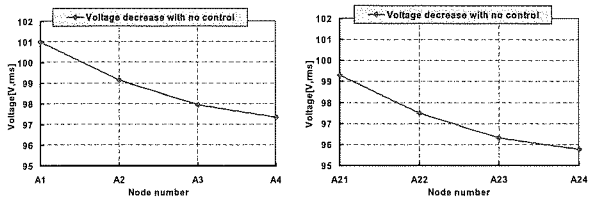
(a) Node A_1 to A_4 (b) Node A_{21} to A_{24}

Fig. 10 Distribution voltage changes due to load patterns.

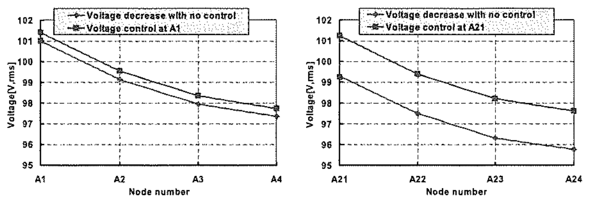
In the light load with reverse power flow condition, 20 PV systems from node A_1 to A_4 connect with pole transformer in the Fig. 9 (a). The simulation result of voltage increase pattern is shown in Fig. 10 (a). In the Fig. 9 (b), 20 PV systems from node A_{21} to A_{24} connect with pole transformer. The simulation result of voltage increase pattern is shown in Fig. 10 (b). Each PV house generates 3[kW] power. 20 PV houses totally generate 60[kW] and then 10[kW] supplies to the light load condition. The remaining 50[kW] flows to the pole transformer. Thus, total reverse power is the same as pole transformer capacity. When the reverse power flows from clustered PV system, the distribution low-voltage is increased 101[V,rms] at node A_1 to 106.15[V,rms] at node A_{24}.

4. 2 Voltage decrease control using D-UPFC

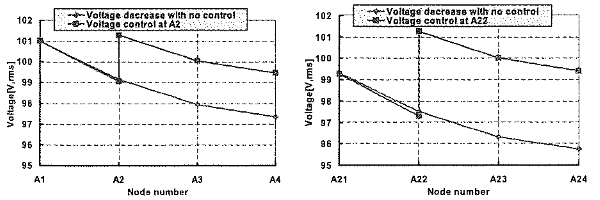
In the Fig. 11, D-UPFC voltage control during voltage decrease phenomenon of forward power flow condition is simulated. As mentioned Fig. 10, heavy load affects voltage decrease in the distribution system. The simulation condition is the same as Fig. 10 thus, the voltage decrease from node A_1 to A_4 is 101[V,rms] to 97.4[V,rms], respectively. The voltage decrease from node A_{21} to A_{24} is 99.3[V,rms] to 95.8[V,rms], respectively. Fig. 11 (a) and (b) show the voltage decrease before injecting D-UPFC. In the Fig. 11 (c) to (j), D-UPFC controls the voltage to 101[V,rms] at its installation place. The controlled voltage ranges are 101.4[V,rms] at node A_1 to 101.3[V,rms] at node A_{24}. D-UPFC assists the voltage patterns with keeping in the distribution voltage range.



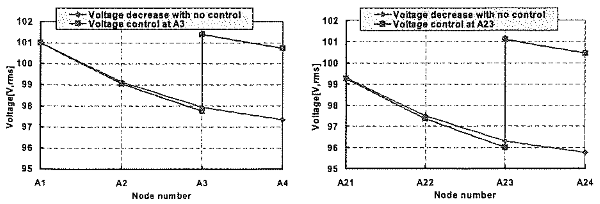
(a) Node A_1 to A_4 with no control (b) Node A_{21} to A_{24} with no control



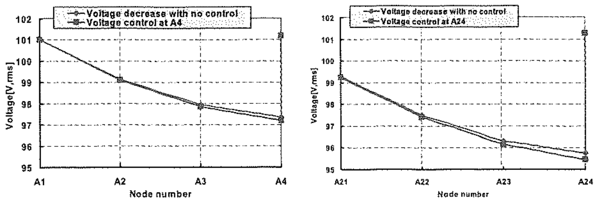
(c) Node A_1 to A_4 with control at A_1 (d) Node A_{21} to A_{24} with control at A_{21}



(e) Node A_1 to A_4 with control at A_2 (f) Node A_{21} to A_{24} with control at A_{22}



(g) Node A_1 to A_4 with control at A_3 (h) Node A_{21} to A_{24} with control at A_{23}



(i) Node A_1 to A_4 with control at A_4 (j) Node A_{21} to A_{24} with control at A_{24}

Fig. 11 Voltage decrease control using D-UPFC.

Fig. 12 shows the D-UPFC waveform at node A24 when voltage decrease occurs from 0[s].

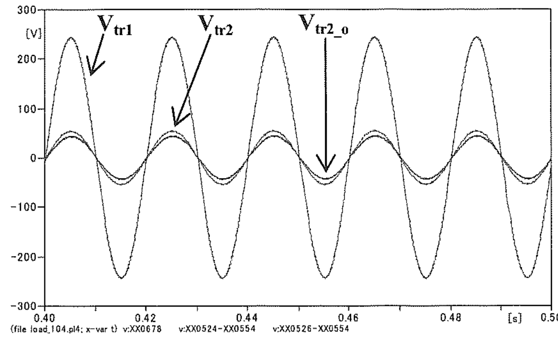
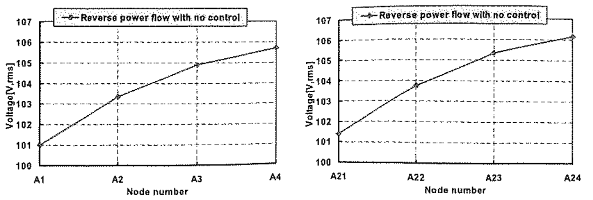


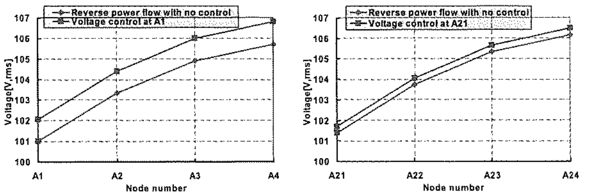
Fig. 12 D-UPFC voltage waveforms during voltage decrease.

4. 3 Voltage increase control using D-UPFC

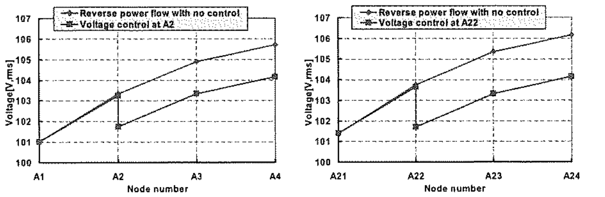
In the Fig. 13, D-UPFC voltage control during voltage increase phenomenon of reverse power flow condition is simulated. As mentioned Fig. 10, light load with reverse power flow affects voltage increase in the distribution system. The simulation condition is the same as Fig. 10. The voltage increase from node A_1 to A_4 is 101[V,rms] to 105.7[V,rms], respectively. The voltage increase from node A_{21} to A_{24} is 101.5[V,rms] to 106.2[V,rms], respectively. Fig. 13 (a) and (b) show the voltage increase before injecting D-UPFC. In the Fig. 13 (c) to (j), D-UPFC controls the voltage to 101[V,rms] at its installation place. After D-UPFC control, the voltage patterns during voltage increase are regulated. The controlled voltage ranges are 102.1[V,rms] at node A_1 to 101[V,rms] at node A_{24}. Thus, D-UPFC assists the voltage patterns with holding in the distribution voltage range.



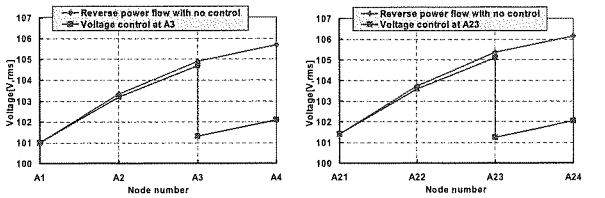
(a) Node A_1 to A_4 with no control (b) Node A_{21} to A_{24} with no control



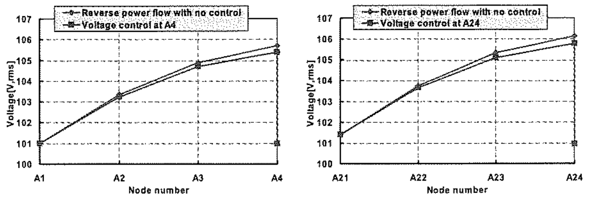
(c) Node A_1 to A_4 with control at A_1 (d) Node A_{21} to A_{24} with control at A_{21}



(e) Node A_1 to A_4 with control at A_2 (f) Node A_{21} to A_{24} with control at A_{22}



(g) Node A_1 to A_4 with control at A_3 (h) Node A_{21} to A_{24} with control at A_{23}



(i) Node A_1 to A_4 with control at A_4 (j) Node A_{21} to A_{24} with control at A_{24}

Fig. 13 Voltage increase control using D-UPFC.

Figure 14 shows the D-UPFC waveforms at node A24 when voltage increase happens due to reverse power flow from 0.02[s].

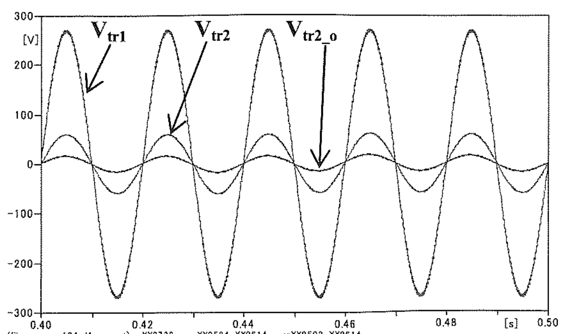


Fig. 14 D-UPFC voltage waveforms during voltage increase.

5. Conclusion

This paper proposes distribution voltage control using D-UPFC during forward power flow and reverse power flow condition. D-UPFC consists of a transformer and bi-directional ac-ac converter. The transformer maintains a part of reference voltage and bi-directional ac-ac converter regulates the voltage to keep the reference voltage. Bi-directional ac-ac converter provides direct ac to ac conversion without storing energy. In the case study, D-UPFC controls the voltage not all distribution nodes but it controls the voltage at its installation site. Thus, D-UPFC assists the voltage patterns with holding inside the distribution voltage range. Finally, voltage sags or swells due to rapidly changing irradiation and load condition in the clustered PV system should be prevented using proposed D-UPFC. Thus, dynamic characteristic of D-UPFC voltage control is verified in the future study.

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