Case study of distrubution-unified power flow controller (D-UPFC) in the clustered PV system

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Abstract—This paper shows the case study of D-UPFC in the clustered PV system. D-UPFC mainly controls distribution voltage and thus, it is installed in the low-voltage distribution system connects with clustered PV system. Proposed D-UPFC topology is shown and compared with existing topology. The proposed topology can decrease the transformer capacity compared with existing topology. In the case study, voltage control and dynamic characteristic of D-UPFC are analyzed. Forward power flow, reverse power flow, and load power factor change conditions are simulated using ATP-EMTP tool.

I. 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 voltage 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.

This paper shows the case study of D-UPFC in the distribution system. D-UPFC is a voltage controller in the low-voltage distribution system. When the voltage decrease is happened due to load consumption power low, D-UPFC controls the voltage rapidly. Also, when voltage increase condition due to reverse power flow from clustered PV system occurs, D-UPFC regulates the distribution voltage.

Proposed D-UPFC topology is compared with existing D-UPFC topology. Proposed topology can decrease transformer size, weight, and capacity because it uses only one secondary side winding. Using this proposed topology, the case study of the distribution model is performed. Distribution voltage control during RL load condition and reverse power flow condition is simulated. The dynamic voltage control due to load power change and reverse power flow is also verified using ATP-EMTP software.

II. D-UPFC THEORY

A. Proposed Topology

D-UPFC consists of transformer and bi-directional ac-ac converter in the low-voltage distribution system. The transformer of the existing D-UPFC topology is divided one primary side and two secondary sides. Bi-directional ac-ac converter is connected in the upper side of the secondary. Fig. 1 shows the existing D-UPFC topology [2,3].

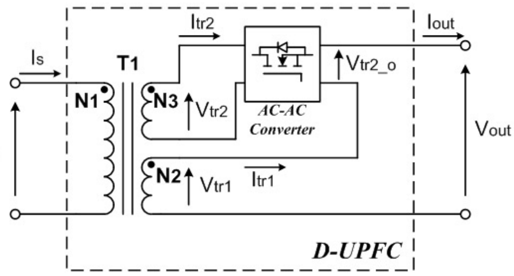


Fig. 1: Existing D-UPFC topology

D-UPFC output voltage equation can be expressed,

$$V_{out} = \frac{N_2 + (D \times N_3)}{N_1} \times V_s = V_{tr1} + (D \times V_{tr2}) = V_{tr1} + V_{tr2\_o} \quad (1)$$

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

Transformer of the proposed topology is divided one primary side and one secondary side. Tap voltage N_1' of primary side is added to secondary side voltage. It is similar to auto-transformer topology. Proposed D-UPFC topology is shown in Fig. 2.

D-UPFC output voltage equation can be expressed,

$$V_{out} = \frac{N_1' + (D \times N_2)}{N_1} \times V_s = V_{tr1} + (D \times V_{tr2}) = V_{tr1} + V_{tr2\_o} \quad (2)$$

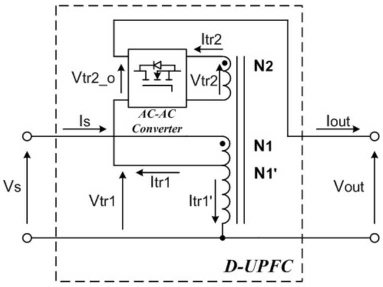


Fig. 2: Proposed D-UPFC topology

Transformer turn's ratio N_1' is the tap which is located in the primary side. Thus, Proposed D-UPFC topology can decrease the transformer size, weight and capacity compared with the existing topology.

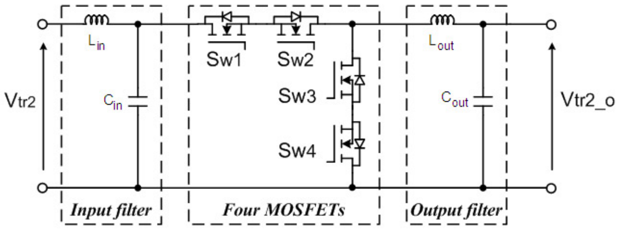


Fig. 3: Bi-directional ac-ac converter circuit

Bi-directional ac-ac converter from the Fig. 2 is shown in Fig.3. The equation of this converter is,

$$V_{tr2\_o} = D \times V_{tr2} \tag{3}$$

B. Voltage Control Method

D-UPFC input voltage V_{in} is always controlled by reference voltage V_{ref_dc}. V_{in} is changed from ac to dc through RMS function. V_{ref_dc} is 202[V,rms], which is low-voltage distribution system voltage. Error voltage V_{error} between V_{in} and V_{ref_dc} is through PI compensator. V_{ref_duty} which is the reference duty of ac-ac converter is added to V_{error_pi}. V_{pwm} compares with V_{tri} in the PWM function. Switches S_{w1} to S_{w4} are operated by PWM function. D-UPFC voltage control block is shown in Fig. 4.

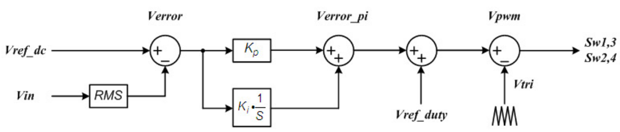


Fig. 4: D-UPFC voltage control block

Bi-directional ac-ac converter can directly transfer ac power to ac power without large energy storage devices. Also, it can control the voltage during power flow change and load change conditions. These conditions are realized using the switching patterns [3, 4].

Considering the clustered PV system connects with low-voltage distribution system, the power flow and load power factor should be changed. Forward power flow, reverse power flow and load power factor change can be expressed using phase diagram. Fig. 5 shows the phase diagram of input voltage and output current relation in the bi-directional ac-ac converter.

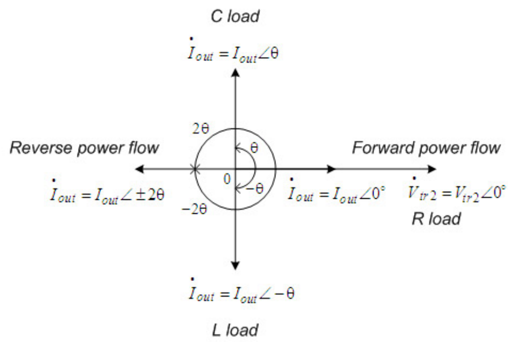
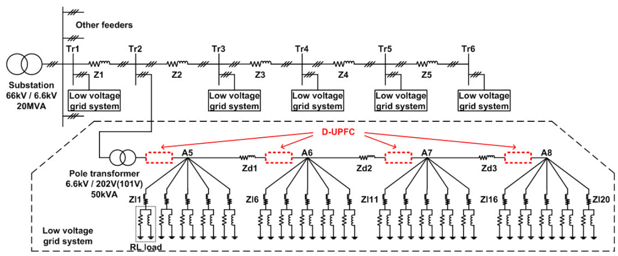


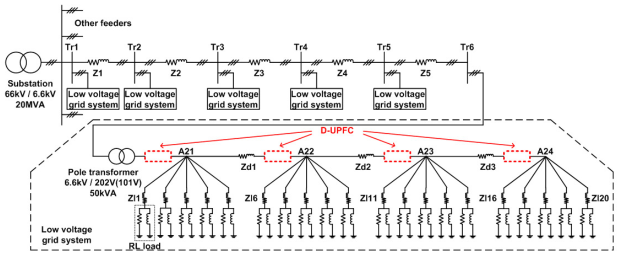
Fig. 5: AC-AC converter input voltage and output current phase diagram considering power flow and load power factor

III. CASE STUDY

D-UPFC voltage control in the low-voltage distribution system is shown. Voltage decrease and increase control are simulated considering load power factor change. D-UPFC dynamic voltage control also simulated using ATP-EMTP.



(a) Node A_5 to A_8 of the distribution model

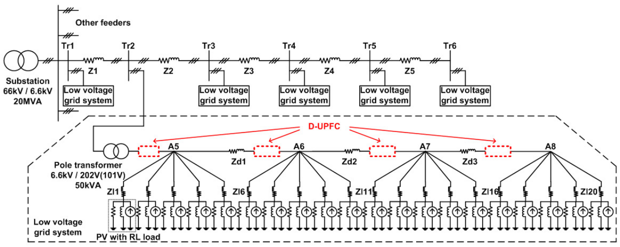


(b) Node A_{21} to A_{24} of the distribution model

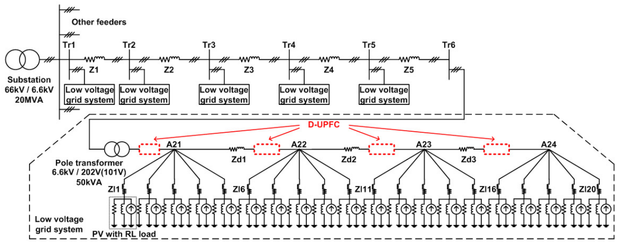
Fig. 6: Distribution model for voltage decrease condition in the RL load

D-UPFC simulation models are shown in Fig. 6 and 7. They are assumed the residential area of Japan. Detailed model explanation is shown in reference [2]. Fig. 6 shows voltage decrease model due to heavy load condition.

D-UPFC installation is shown from A_5 to A_8 of Tr_2, from A_{21} to A_{24} of Tr_6 pole transformer.



(a) Node A_5 to A_8 of the distribution model



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

Fig. 7: Distribution model for voltage increase condition in the RL load with clustered PV system

Fig. 7 shows the voltage increase model due to reverse power flow from clustered PV system. D-UPFC installation is shown from A_5 to A_8 of Tr_2, from A_{21} to A_{24} of Tr_6 pole transformer.

Table 1 shows the distribution model parameters. Power factor is assumed 0.9 in the RL load condition. Capacity of a PV system is regarded as 3[kW].

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+j2.028[Ω] (p.f. 0.9)
	Heavy load	1.02+j0.507[Ω] (p.f. 0.9)
Each PV power		3[kW]

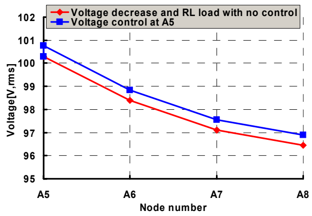
D-UPFC parameters are shown in Table 2. The maximum D-UPFC voltage control range is ±20.2[V,rms] from transformer voltage tap N_2. Input and output LC filters reduce input current and output voltage harmonics [5]. D-UPFC output is the same as distribution system voltage 202[V,rms] during normal mode.

TABLE 2. D-UPFC parameters

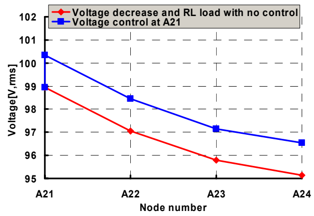
V_S	202[V,rms]	C_{in} & C_{out}	50[μF]
N_1: N_1': N_2	1:0.9:0.2	V_{ref_dc}	202[V,rms]
V_{tr1}	181.8[V,rms]	PI gain	K_p=0.025 K_i=0.001
V_{tr2}	40.4[V,rms]	Switching freq.	20[kHz]
L_{in} & L_{out}	50[μH]	V_{ref_duty}	0.5

A. Voltage decrease control

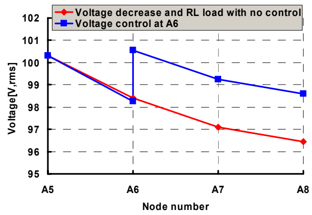
Voltage decrease control is shown in Fig. 8. These simulation results are performed when heavy load is connected to the distribution system. Heavy load parameters are shown in Table 1.



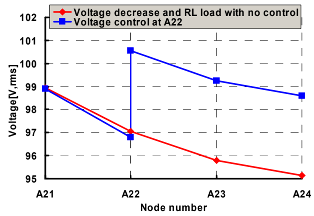
(a) D-UPFC control at A_5



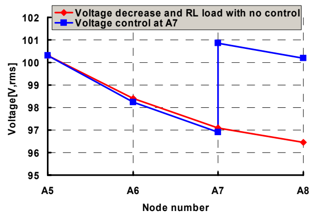
(b) D-UPFC control at A_{21}



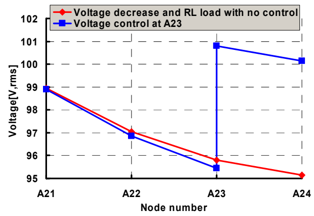
(c) D-UPFC control at A_6



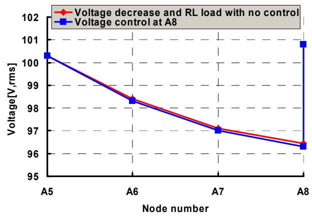
(d) D-UPFC control at A_{22}



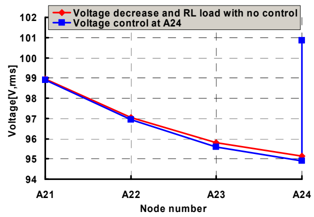
(e) D-UPFC control at A_7



(f) D-UPFC control at A_{23}



(g) D-UPFC control at A_8

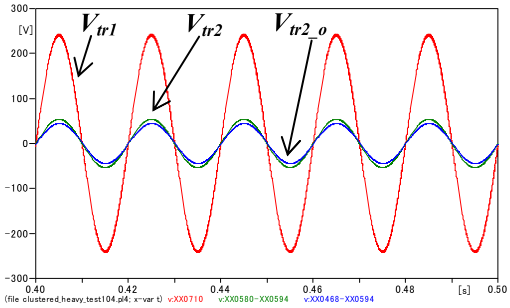


(h) D-UPFC control at A_{24}

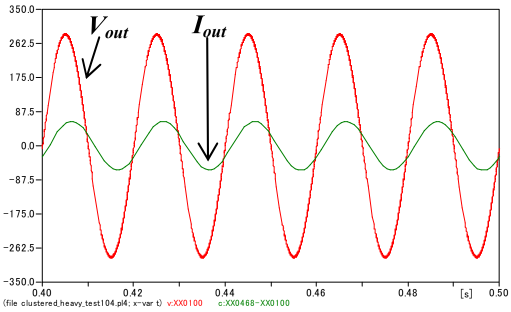
Fig. 8: Voltage decrease control in the RL load condition

As the Fig. 6, D-UPFC is installed in the secondary of the pole transformer. The low-voltage distribution voltage range is 202±20 (101±6)[V,rms]. Fig. 8 shows the 100[V,rms] line results. Before the D-UPFC control voltage decrease from node A_5 (a) to A_8 (g) is from 100.3[V,rms] to 96.5[V,rms], respectively. However, D-UPFC controls 100.7[V,rms] to 100.8[V,rms] from node A_5 to A_8, respectively. Also, voltage decrease from node A_{21} (b) to A_{24} (h) is from 99[V,rms] to 95.2[V,rms], respectively. These voltage decreases are controlled from 100.4[V,rms] to 100.9[V,rms], respectively. Thus, D-UPFC controls distribution voltage to reference voltage at the installation site.

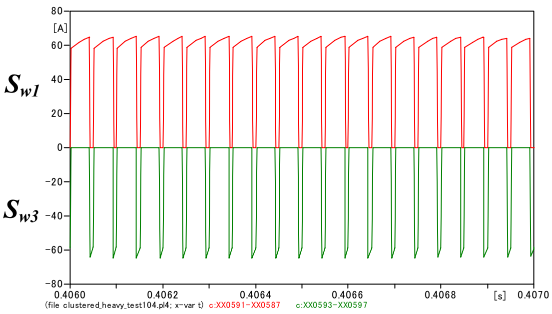
Fig. 9 shows D-UPFC inner voltage (V_{tr1}, V_{tr2}, V_{tr2_o}), output voltage (V_{out}), output current (I_{out}), and ac-ac conveter switches (S_{w1} to S_{w4}) current waveforms at node A_{24}. When the voltage decrease occurs caused by heavy load the bi-directional ac-ac converter output voltage V_{tr2_o} increases in the (a) of Fig. 9. D-UPFC output current phase lags to output voltage in the (b) of Fig. 9. Also, switches from S_{w1} to S_{w4} show the current waveforms without any problem in the (c) and (d) of Fig. 9.



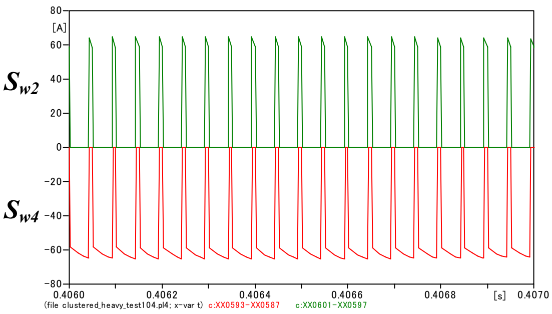
(a) D-UPFC inner voltage V_{tr1}, V_{tr2}, V_{tr2_o}



(b) D-UPFC output voltage V_{out}, output current I_{out}



(c) AC-AC converter switch S_{w1}, S_{w3}

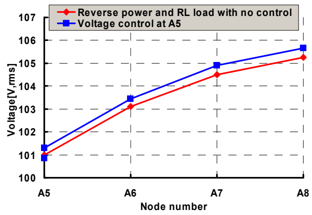


(d) AC-AC converter switch S_{w2}, S_{w4}

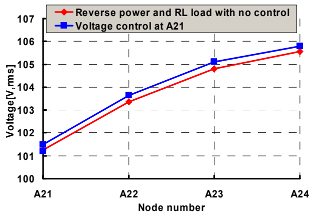
Fig. 9: Voltage and current waveforms during voltage decrease at A_{24}

B. *Voltage increase control*

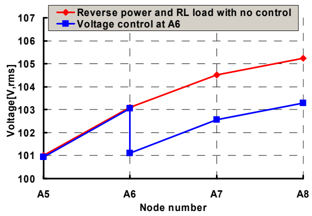
Fig. 10 shows the D-UPFC voltage control during voltage increase from PV reverse power flow. As shown in Table 1 and 2, parameters are used in the simulation. Voltage increase from node A_5 (a) to A_8 (g) is 101[V,rms] to 105.3[V,rms], respectively. These node voltages are controlled through D-UPFC from 101.3[V,rms] to 101.1[V,rms], respectively. Also, voltage increase from node A_{21} (b) to A_{24} (h) is 101.3[V,rms] to 105.6[V,rms], respectively. D-UPFC controls the voltages from 101.5[V,rms] to 101.3[V,rms], respectively. From the Fig. 10, D-UPFC controls the distribution voltage at the installation site as the voltage decrease control.



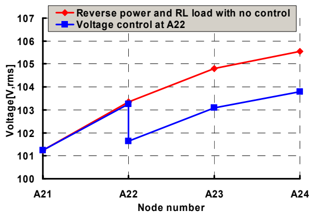
(a) D-UPFC control at A_5



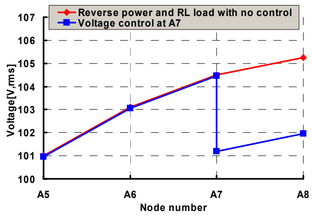
(b) D-UPFC control at A_{21}



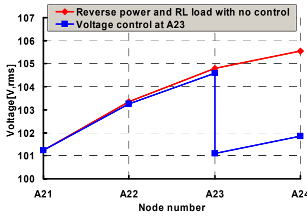
(c) D-UPFC control at A_6



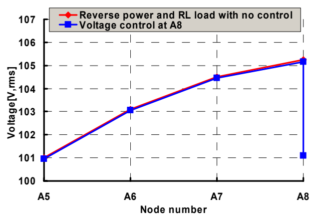
(d) D-UPFC control at A_{22}



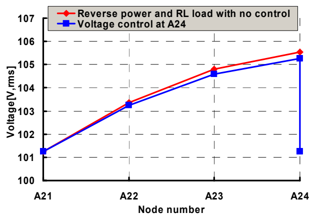
(e) D-UPFC control at A_7



(f) D-UPFC control at A_{23}



(g) D-UPFC control at A_8

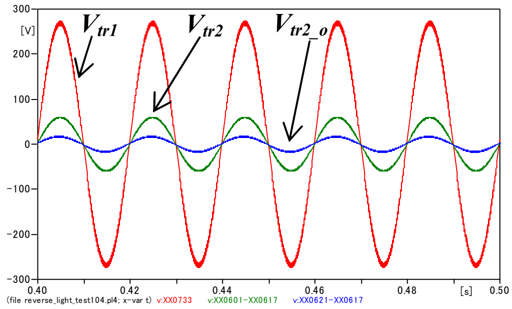


(h) D-UPFC control at A_{24}

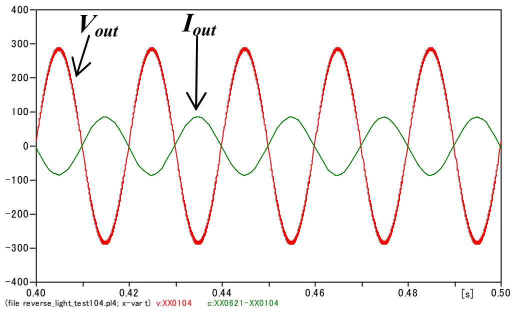
Fig. 10: Voltage increase control in the reverse power flow condition

Fig. 11 shows D-UPFC inner voltage (V_{tr1}, V_{tr2}, V_{tr2_o}), output voltage (V_{out}), output current (I_{out}), and ac-ac conveter switches (S_{w1} to S_{w4}) current waveforms at node A_{24}. In the D-UPFC control, ac-ac converter output voltage V_{tr2_o} is decreased in the (a) of Fig. 11. The second waveforms show the V_{out} and I_{out} of D-UPFC. Here, I_{out} phase is 180° different from V_{out} due to reverse power flow condition. Even though the load power factor is 0.9, I_{out} is not affected by load current because PV output current was large and grid-connected.

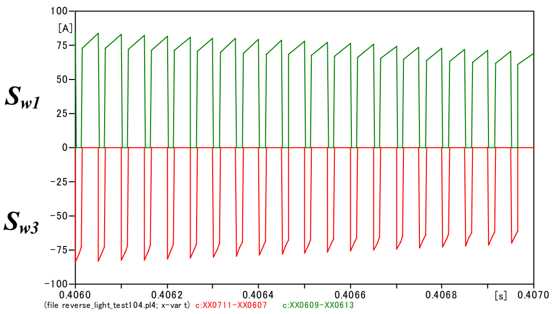
Switches which are from S_{w1} to S_{w4} current waveforms (c) and (d) of Fig. 11 perform with no problem during operation.



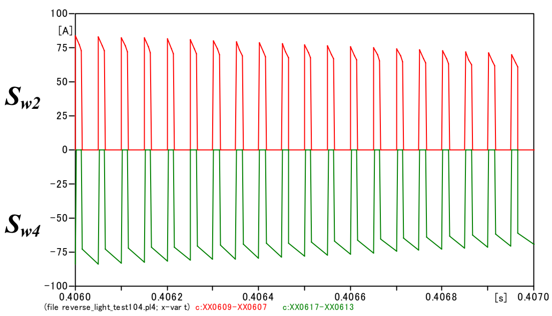
(a) D-UPFC inner voltages V_{tr1}, V_{tr2}, V_{tr2_o}



(b) D-UPFC output voltage V_{out}, output current I_{out}



(c) AC-AC converter switch S_{w1}, S_{w3}

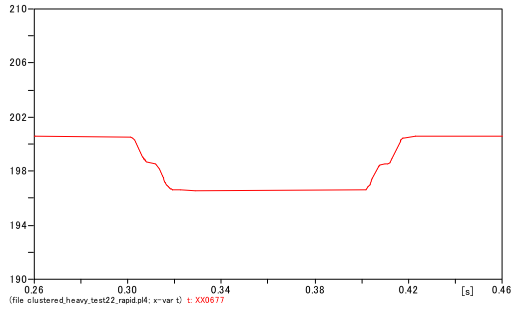


(d) AC-AC converter switch S_{w2}, S_{w4}

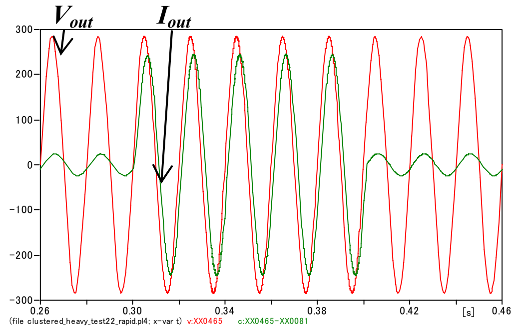
Fig. 11: Voltage and current waveforms during voltage increase at A_{24}

C. Dynamic voltage control

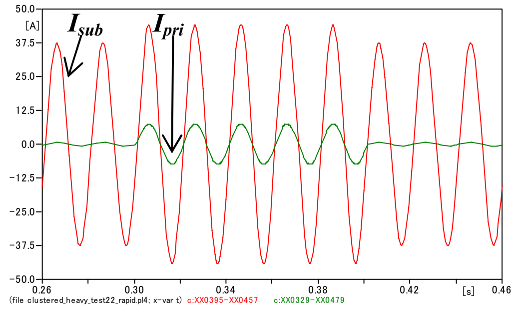
Rapid voltage change is always occurred in the low-voltage distribution system due to load consumption power and PV reverse power. Thus, D-UPFC should control this rapid voltage change in order to prevent voltage problem in the distrution line. Dynamic voltage control during the voltage decrease condition is shown in Fig. 12.



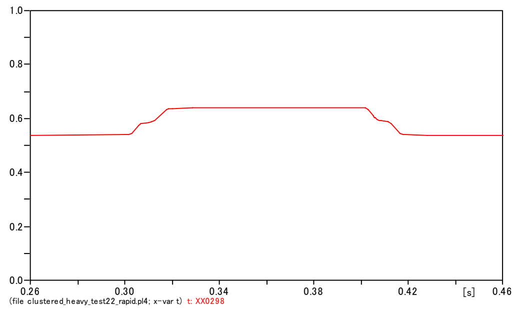
(a) D-UPFC input voltage V_{in_dc}



(b) D-UPFC output voltage V_{out}, output current I_{out}



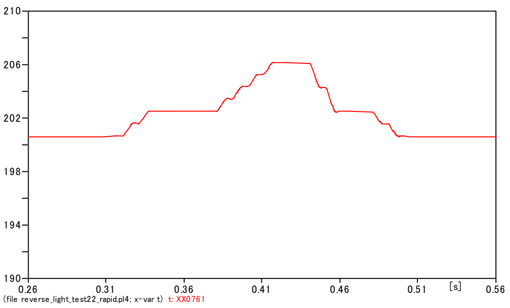
(c) Substation current I_{sub}, primary current of pole transformer I_{pri}



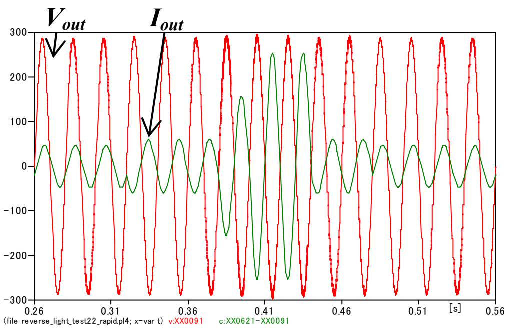
(d) AC-AC converter duty cycle

Fig. 12: Load consumption power change from 0.3[s] to 0.4[s] and D-UPFC installation at node A_6

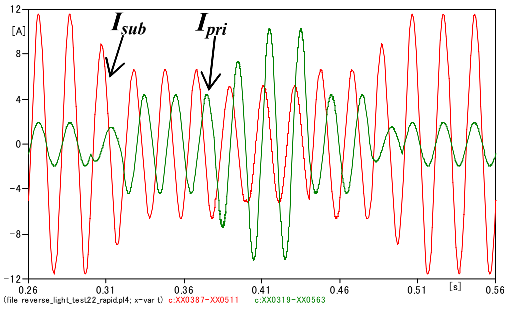
From the Fig. 6 (a), load consumption power changes 4.9[kW] to 34.6[kW] between 0.3[s] and 0.4[s] at pole transformer. In the Fig. 12 (a), distribution voltage at node A_6 changes 200.5[V,rms] to 196.5[V,rms] during voltage decrease period. Also, it shows the voltage decrease as the rms value. Fig. 12 (b) shows the D-UPFC output voltage, current waveforms and D-UPFC controls the voltage to 201.1(100.55)[V,rms] during 0.3[s] to 0.4[s]. Fig. 12 (c) shows the substation output current and pole transformer primary current. Here, current from the substation increases due to heavy load during 0.3[s] to 0.4[s]. Fig. 12 (d) shows the ac-ac converter duty ratio and it controls the D-UPFC output voltage during 0.3[s] to 0.4[s].



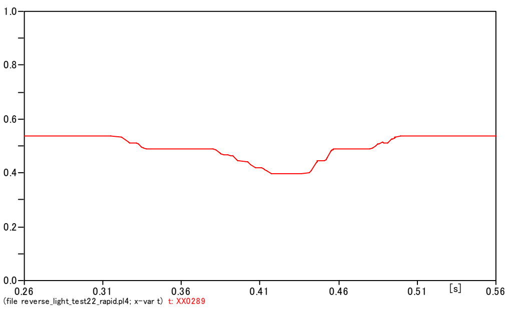
(a) D-UPFC input voltage V_{in_dc}



(b) D-UPFC output voltage V_{out}, output current I_{out}



(c) Substation current I_{sub}, pole transformer primary current I_{pri}



(d) AC-AC converter duty cycle

Fig. 13: PV reverse power flow during 0.32[s] to 0.48[s] and D-UPFC installation at node A_6

Dynamic voltage control during the voltage increase condition is shown in Fig. 13. From the Fig. 7 (a), PV reverse power increases 9[kW] to 47.6[kW] at pole transformer. PV reverse power flows at random from 0.32[s] to 0.48[s]. The maximum reverse current of PV output is 236[A,rms]. Distribution voltage at node A_6 changes 200.5[V,rms] to 206.14 (103.07)[V,rms] during reverse power flow period. Fig. 13(a) shows the voltage increase as the rms value. Fig. 13 (b) shows the D-UPFC output voltage, current waveforms and D-UPFC controlling the voltage is 203.3 (101.65)[V,rms]. Fig. 13 (c) shows the substation output current and pole transformer primary current. Substation output current decreases 0.32[s] to 0.48[s], because the reverse current of PV output flows to other pole transformers. Finally, Fig. 13 (d) shows the ac-ac converter duty ratio and it controls the D-UPFC output voltage during 0.32[s] to 0.48[s].

IV. Conclusion

This paper shows distribution voltage control using the proposed D-UPFC topology in the distribution model. D-UPFC controls the distribution voltage during voltage decrease and increase conditions. Also, dynamic characteristic of D-UPFC voltage control is verified through the simulation results. D-UPFC protection study will be performed soon.

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