Case study of distribution-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. The proposed D-UPFC topology is shown and compared with the existing topology. The proposed topology can decrease 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 the ATP-EMTP tool.

I. INTRODUCTION

In the power flow condition, faults occurring in power distribution systems or facilities in plants generally cause 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 concern 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 power 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].

D-UPFC output voltage equation can be expressed,

\[ V_{out} = \frac{N_2}{N_1} \times (D \times V_{r2}) + (V_{r1} + V_{r2-o}) \]  

(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 \( N_{r'} \) 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,

\[ V_{out} = \frac{N_1 \times (D \times V_{r2})}{N_1} \times V_{r1} + (D \times V_{r2}) = V_{r1} + V_{r2-o} \]  

(2)
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.

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

\[ V_{r2} = D \times V_{r2} \]  

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 200[V,rms], which is low-voltage distribution system voltage. Error voltage \( V_{error} \) between \( V_{in} \) and \( V_{ref \_dc} \) is through PI compensator. \( V_{error \_dc} \) which is the reference duty of ac-ac converter is added to \( V_{error \_ac} \). \( V_{pwm} \) compares with \( V_{in} \) in the PWM function. Switches \( S_{1} \) to \( S_{4} \) are operated by PWM function. D-UPFC voltage control block is shown in Fig. 4.

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].

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.

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.
D-UPFC installation is shown from $A_j$ to $A_8$ of $Tr_2$, from $A_{2j}$ to $A_{28}$ of $Tr_8$ pole transformer.

**TABLE 1. Distribution model parameters**

<table>
<thead>
<tr>
<th>Substation</th>
<th>66kV/0.6kV, 20MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole transformer</td>
<td>6.6kV/202V(101V), 50kVA</td>
</tr>
<tr>
<td>HV line impedance($Z_a$ to $Z_b$)</td>
<td>0.626+0.754[0/2km]</td>
</tr>
<tr>
<td>LV line impedance($Z_{a1}$ to $Z_{a2}$)</td>
<td>0.025+0.020[0/40m]</td>
</tr>
<tr>
<td>Lead-in wire imp.($Z_{a1}$ to $Z_{a2}$)</td>
<td>0.055+0.037[0/20m]</td>
</tr>
<tr>
<td>Total load</td>
<td>Light load: 4.08+0.028[p.f. 0.9]</td>
</tr>
<tr>
<td></td>
<td>Heavy load: 1.02+0.507[p.f. 0.9]</td>
</tr>
<tr>
<td>Each PV power</td>
<td>3[kW]</td>
</tr>
</tbody>
</table>

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 $A_j$ (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 $A_j$ to $A_8$, respectively. Also, voltage decrease from node $A_{2j}$ (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.

**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.
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 converter switches \((S_{ac1} \text{ to } S_{ac3})\) current waveforms at node \(A_{2g}\). 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 \(S_{ac1}\) to \(S_{ac3}\) show the current waveforms without any problem in the (c) and (d) of Fig. 9.

**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 \(A_{1}(a)\) to \(A_{6}(g)\) is 101.2[V, rms] to 105.1[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 \(A_{2g}(b)\) to \(A_{2h}(h)\) 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.

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 converter switches \((S_{ac1} \text{ to } S_{ac3})\) current waveforms at node \(A_{2p}\). 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 $V_{inv}$ 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.

Power and PV reverse power. Thus, D-UPFC should control this rapid voltage change in order to prevent voltage problem in the distribution line. Dynamic voltage control during the voltage decrease condition is shown in Fig. 12.

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. 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 condition.

Fig. 11: Voltage and current waveforms during voltage increase at $A_6$

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 condition.
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].

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 $A_e$ 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.

ACKNOWLEDGMENT

This research has been carried as a part of “Autonomy-Enhanced PV Cluster” project and special thanks for financial support of NEDO.

REFERENCES