VOLTAGE SAG/SWELL CONTROLLER BY MEANS OF D-UPFC IN THE DISTRIBUTION SYSTEM

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ABSTRACT

A power quality issue, especially, voltage problem is the vital concern in most distribution system today. So far, the voltage problem is mainly from under-voltage (voltage sag) condition due to a short circuit or fault. Recently, renewable energy such as photovoltaic (PV) system affects over-voltage (voltage swell) condition caused by its reverse power flow at daylight.

In this paper, proposed Distribution-Unified Power Flow Controller (D-UPFC) for preventing both voltage sag and swell conditions is discussed. The proposed scheme consists of an AC chopper, a switch and a series transformer. The AC chopper generates compensation power when voltage sag or swell condition happens. The secondary and tertiary parts of a series transformer connect with switches for controlling voltage sag or swell. D-UPFC does not need any energy storage devices such as large capacitors or inductors and it provides fast compensation.Simulation results show D-UPFC controls voltage concerns in the distribution system.

INTRODUCTION

Power quality in the distribution system is the important issue for industrial, commercial and residential applications today. The voltage problem is mainly considered from under-voltage (voltage sag) condition caused by short circuit or fault somewhere in the distribution system. Preventing voltage sag condition, many researches have been implemented.

Among the most common are tap-changing transformers, which are the types of voltage regulators used in today's distribution system. However, these methods have significant shortcomings. For instance, the tap-changing transformer requires a large number of thyristors, which results in highly complex operation for fast response. Furthermore, it has very poor transient voltage rejection, and only has an average response time [1].

Recently, renewable energy such as photovoltaic (PV) system is installed in many places. Although PV system has many advantages for future view, a lot of PV systems which are installed in the residential areas together can cause over-voltage (voltage swell) condition due to their reverse power flows. Like tap changing transformer from existing technology, SVR (Step Voltage Regulator) which consists of autotransformer with line drop compensator controls voltage swell as well as voltage sag. Even though SVR controls distribution system's voltage, SVR can not install in every pole transformer place, because we should consider the price of the product. Also, future distribution system will be changed to increasing the installation of renewable energy, especially PV system. Thus, future distribution system might be more complex and there are occuring many problems than today. To solve voltage variations, voltage sag and swell, the author proposes Distribution-Unified Power Flow Controller (D-UPFC) in the distribution system. D-UPFC concept and its function shows in Figure 1.

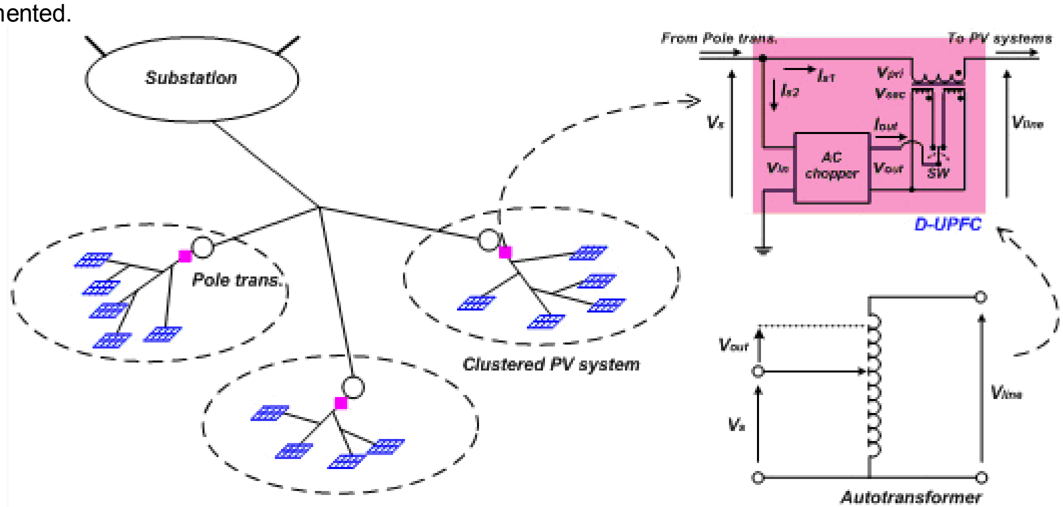

Fig. 1. D-UPFC concept and its function in the distribution system.

It consists of an AC chopper with a series transformer. It places after pole transformer and it controls voltage sag and swell. D-UPFC is also regared as a transformer and thus, pole transformer with D-UPFC function is the same as autotransformer.

This paper discusses the proposed D-UPFC concept and shows distribution voltage control using simulation tool. An AC chopper generates control voltage when voltage sag or swell occurs and a switch connected series transformer selects voltage compensation or regulation. D-UPFC does not use any large energy storage, such as large capcitor or inductor and it fast controls distribution system voltage.

PROPOSED CONCEPT

The concept of D-UPFC is to control distribution system voltage during voltage sag or swell condition. D-UPFC equivalent circuit in order to control voltage effectively is shown in Fig. 2.

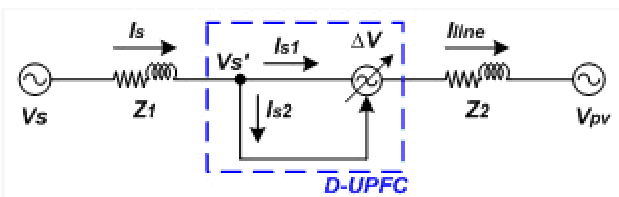

Fig. 2. The equivalent circuit of D-UPFC with clustered PV system.

When voltage variation ΔV happens due to voltage sag or swell in the D-UPFC, the D-UPFC output ΔP is given,

$$\Delta P = \Delta V \times I_{s1} \quad (1)$$

Also, D-UPFC input current I_{s2} due to voltage variation is,

$$I_{s2} = (\frac{\Delta V}{V_s'}) I_{s1} \quad (2)$$

Using Kirchhoff's current law, pole trans. current I_s is given,

$$I_s = I_{s1} + I_{s2} = (1 + \frac{\Delta V}{V_s'}) I_{s1} \quad (3)$$

D-UPFC input voltage V_s' is given,

$$V_s' = V_s - (Z_1 \times I_s) = V_s - Z_1 (1 + \frac{\Delta V}{V_s'}) I_{s1} \quad (4)$$

where, V_s is pole tr. Voltage, V_{pv} is clustered PV system voltage, Z_1 and Z_2 are line impedances (however, Z_1 is very small because D-UPFC connects with pole trans. voltage V_s in the same pole)

Through eq. (1) to (4), the effective D-UPFC control should agree with eq. (5).

$$\left| \Delta V_s' \right| \le \left| \Delta V \right| \quad (5)$$

where, $\Delta V_s'$ is the variation value of V_s'

D-UPFC SCHEME AND CONTROL

D-UPFC scheme

D-UPFC topology and normal state operation show in Fig. 3. D-UPFC consists of an AC chopper, a series transformer and a switch. D-UPFC does not generate power when distribution voltage is at normal state. Switch S_2 and S_3 of AC chopper are ON and also SW_1 always connects with a series transformer. Also, AC chopper operates with Pulse Width Modulation (PWM) control.

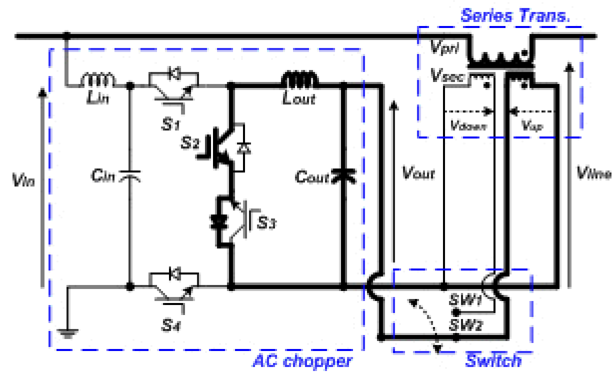

Fig. 3. D-UPFC topology and its normal state operation.

When voltage sag or swell condition happens, D-UPFC performs to generate voltage in order to regulate distribution system voltage. AC chopper output voltage V_{out} is always less than the input voltage V_{in}.

$$V_{out} \le V_{in} \times D \quad (6)$$

where, D is duty ratio

Table 1 shows D-UPFC switches operation during voltage control state.

Table 1. D-UPFC switches operation during voltage control state

** means current flows through reverse diode of the switch*

Mode	Phase	AC chopper				Series trans.	
		S1	S2	S3	S4	SW1	SW2
Voltage UP	+	ON	OFF	OFF	***ON**	OFF	ON
		OFF	***ON**	ON	OFF	OFF	ON
	-	***ON**	OFF	OFF	ON	OFF	ON
		OFF	ON	***ON**	OFF	OFF	ON
Voltage DOWN	+	ON	OFF	OFF	***ON**	ON	OFF
		OFF	***ON**	ON	OFF	ON	OFF
	-	***ON**	OFF	OFF	ON	ON	OFF
		OFF	ON	***ON**	OFF	ON	OFF

D-UPFC control

D-UPFC senses input voltage, line voltage and line current. Input voltage is the reference voltage because it connects with pole trans. voltage V_s. Line voltage and current represent the D-UPFC output voltage and output current, respectively. Figure 4 shows D-UPFC control in the distribution system. Input voltage V_{in} and line voltage with line impedance V_{line_sum} for controlling PCC (here, PCC is the next pole apart from the pole transformer) voltage and line current I_{line} are sensed and change to Direct Current (DC) values through Root-Mean-Square (RMS) function.

Next, V_{in} and V_{line} are compared each other and then voltage error V_{error} is calculated. V_{error} then changes to reference voltage V_{ref} through propotional (P) control. In the PWM control, V_{ref} and triangle voltage V_{tri} are compared and then this control supplys switching signals to the AC chopper. Also, SW_1 and SW_2, which decide voltage up or down during compensation mode operation using D-UPFC control. D-UPFC uses the voltage margin in order to control distribution voltage flexibly. Pole transformer's secondary voltage range of Japan is 101±6 [V,rms]. If V_{error} is less than 2[V] of voltage margin, D-UPFC does not operate. Voltage margin equation is shown in eq. (7).

$$\left|V_{in} - V_{line\_sum}\right| < 2[V] \quad (7)$$

where, V_{line_sum} means V_{line} plus line impedance Z_2 voltage V_{z2}

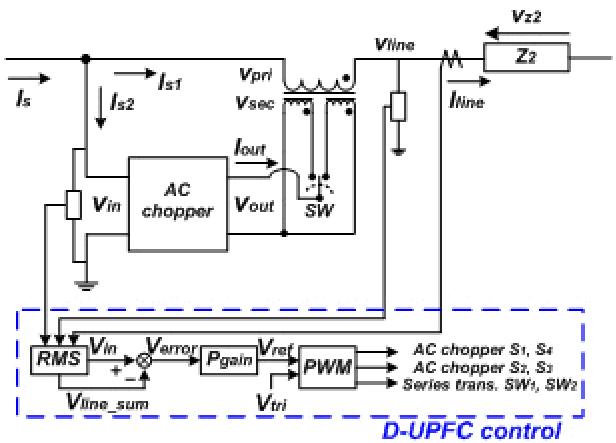

Fig. 4. D-UPFC control in the distribution system.

SIMULATION MODEL AND PARAMETERS

Simulation model

Grid connected D-UPFC simulation model is considered a simple condition. Figure 5 shows the D-UPFC simulation model. This model is analyzed from substation to load area. D-UPFC is installed at the back of pole transformer. Load and clustered PV system are simply fixed after PCC. However, the actual load conditions quiet complicate.

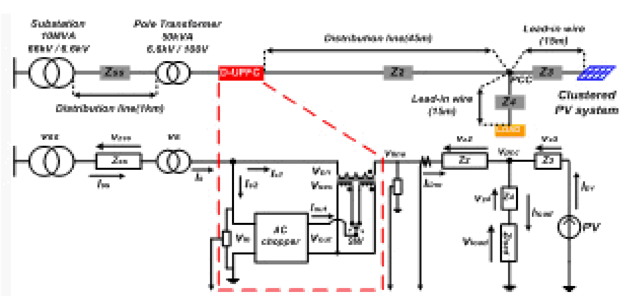

Fig. 5. D-UPFC simulation model.

Simulation model parameters of D-UPFC are shown in Table 2. Line impedance parameters refer to electric company information of Japan. A series transformer turns ratio for compensating voltage sag or swell condition refers to [1], [2]. Input and output filters should reduce the switching frequency harmonics present in the input current i_{s2}, output voltage V_{out}, respectively [3]. In the simulation model, the distance from substation to pole transformer is 1[km]. From pole transformer to PCC is 45[m]. PCC connects with load and the clustered PV system. The lead-in wire distance is 15[m].

Table 2. D-UPFC simulation parameters

V_{ss}	6600[V,rms]
V_s	100[V,rms]
Z_{ss}	0.25+j0.34[Ω/1km]
Z_2	0.011+j0.013[Ω/45m]
Z_3,Z_4	0.00345+j0.00015[Ω/15m]
Z_{load}	10+0.01[Ω]
Substation Tr. [N_{pri}/N_{sec}]	66:1
Distribution Tr. [N_{pri}/N_{sec}]	1:1
Series Tr. [N_{pri}/N_{sec}]	1:3
Input filter	50[μH], 20[μF]
Output filter	75[μH], 30[μF]
Switching frequency	10[kHz]
V_{sag}	0 ~ 4[V,rms]
PV source (I_{pv})	0 ~ 300[A,rms]

RESULTS AND DISCUSSIONS

The purpose of D-UPFC control is that the load area voltages, such as V_{pcc}, V_{load} which are shown in Fig. 5 should be controlled from voltage sag or swell. As mentioned, D-UPFC senses V_{line} and calculates V_{line_sum} using line impedance Z_2. So, V_{line_sum} can be written as eq. (8).

$$V_{line\_sum} = V_{pcc} + (I_{line} \times Z_2) \quad (8)$$

However, Eq. (8) can be only used when power flow is from substation to load area. When reverse power flow occurs eq. (8) changes to eq. (9).

$$V_{line\_sum} = V_{pcc} - (I_{line} \times Z_2) \quad (9)$$

Simulation performs considering both voltage sag and swell conditions. Table 1 shows the simulation result when voltage sag happens. Voltage sag V_{sag} from 0[V,rms] to 4[V,rms] was simulated in the distribution system. V_{in} is the D-UPFC input voltage, V_{line} is the D-UPFC output voltage, and V_{line_sum} is the compensatated D-UPFC output voltage to control V_{pcc}. D-UPFC controls V_{pcc} voltage to 98.6[V,rms] when V_{sag} is 3[V,rms]. V_{sag} voltage from 0[V,rms] to 2[V,rms] does not control V_{pcc} voltage because of voltage margin, which shows eq. (7). However, V_{pcc} was not controlled when V_{sag} was 4[V,rms].

Table 3. Voltage sag result

* All parameters indicate RMS value, '-' means unstable voltage.

Vsag	No D-UPFC control				D-UPFC Control		
	Vin	Vline	Vpcc	Vline_sum	Vline	Vline_sum	Vpcc
0	99.5	99.4	99.3	99.6	99.4	99.4	99.3
1	99.5	98.4	98.33	98.6	98.4	98.4	98.3
2	99.5	97.48	97.37	97.6	97.5	97.5	97.4
3	99.5	96.53	96.42	96.5	***98.8***	***98.8***	***98.6***
4	99.5	95.6	95.5	95.6	-	-	-

In the voltage swell simulation, clustered PV system regarded as the current source. Thus, I_{pv} means clustered

PV system. Voltage swell condition is considered the reverse power flow so that I_{pv} increases from 0[A,rms] to 300 [A,rms]. The same as voltage sag condition, D-UPFC controls V_{pcc} voltage after eq. (7) is implemented. When I_{pv} changed from 150[A,rms] to 300[A,rms], V_{pcc} voltage controlled from 100.1[V,rms] to 102.4[V,rms].

Table 4. Voltage swell result

* All parameters indicate RMS value.

Ipv	No D-UPFC control				D-UPFC Control		
	Vin	Vline	Vpcc	Vline_sum	Vline	Vline_sum	Vpcc
0	99.5	99.4	99.3	99.6	99.4	99.4	99.3
50	99.5	99.5	99.9	100.2	99.5	100.2	99.9
100	99.5	99.6	100.7	101.1	99.6	101.1	100.7
150	99.5	99.9	101.6	102.3	***98.6***	***100.1***	***100.3***
200	99.5	100.3	102.6	103.5	***98.5***	***101.8***	***100.9***
250	99.5	100.7	103.8	104.8	***98.5***	***102.6***	***101.6***
300	99.5	101.3	105.1	106.2	***98.6***	***103.5***	***102.4***

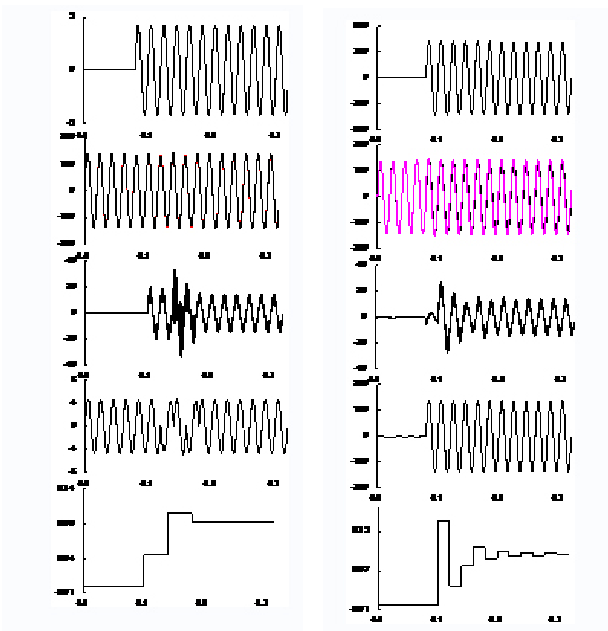

Fig. 6. Voltage sag and swell simulation waveforms (The left graph shows voltage sag 3[V,rms] from 0.08[s], the right graph indicates voltage swell 300[A,rms] from 0.08[s]).

The left of Fig. 6 shows when voltage sag 3[V,rms] occurs at 0.08[s]. The right of Fig. 6 shows when voltage swell I_{pv} 300[A,rms] happens at 0.08[s]. X axis shows simulation time from 0[s] to 0.3[s]. Two simulation results are already shown in Table 3 and 4, respectively. Fig. 6 shows the waveforms of voltage sag and voltage swell simulation. The left-top waveform shows the V_{sag} waveform, input voltage V_{in} and pcc voltage V_{pcc} are shown in the below waveform. Next, the third and fourth waveforms show AC chopper output voltage and current, respectively. Finally, the bottom waveform indicates PWM signal of D-UPFC is shown. Although V_{sag} occurs at 0.08[s], the steady-state condition of PCC voltage becomes steady-state after 0.2[s].

The top-right waveform shows the voltage swell with increasing reverse current I_{pv} from 0.08[s]. In the second graph, V_{in} and V_{pcc} increase instantaneously as I_{pv} increases. In the third waveform, AC chopper output voltage operates from 0.1[s]. However, voltage angle changed because of reverse power flow. The fourth waveform shows AC chopper output current also get effect from I_{pv}. The bottom waveform shows PWM signal of D-UPFC and also the steady-state condition starts after 0.3[s].

Although the author proposes D-UPFC in the distribution system, simulation problems occurred. Also, future study should be needed. Firstly, When voltage sag increases to 4[V,rms], D-UPFC control voltages are unstable. Control gain is not valid to D-UPFC. Secondly, when voltage swell happens, the voltage difference between V_{line_sum} and V_{pcc} occurs and it is shown in Table 4. The reason is that D-UPFC output voltage V_{line} is changed when reverse power flow happens. In the future study, D-UPFC capacity is necessary in order to install with the pole transformer. The difference of D-UPFC output voltage and current angle when power flow changes are essential to research.

CONCLUSIONS

For the reliable voltage control of the future distribution system, D-UPFC proposes in this paper. In this paper, D-UPFC concept and topology show. The basic D-UPFC switching operation mentioned. Voltage margin and voltage compensation method using line impedance introduced. D-UPFC simulation model is used to prove voltage control during voltage sag and swell condition. However, a few problems occur during voltage sag and swell simulations. More study is needed in order to use D-UPFC in the distibution system.

ACKNOWLEDGEMENT

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