# D-UPFC as a Voltage Regulator in the Distribution System

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This paper proposes a voltage controller in order to control under-voltage and over-voltage condition in the distrubution system. The voltage controller, which are called distribution-unified power flow controller (D-UPFC), consists of ac-ac converter and the transformer. D-UPFC does not use any energy storage component or rectifier circuit, and it directly converts ac power to ac power. All pass filter and direct-quadrature (d-q) transformation functions are employed in the D-UPFC control. Also, D-UPFC is located in the pole transformer or any place in the distribution line. Simulation and experiment results show the possibility of controlling under-voltage and over-voltage conditions in the distribution system.

**Keywords**: distribution system, D-UPFC, ac-ac converter, all pass filter, d-q transformation

## INTRODUCTION

In the present power system, the generated power is assumed to feed into the system at the high voltage level and the power is consumed at the low voltage level. Thus, the power direction through a transformer would always be from the high voltage level to the low voltage level [1]. The present power system is shown in Fig. 1.

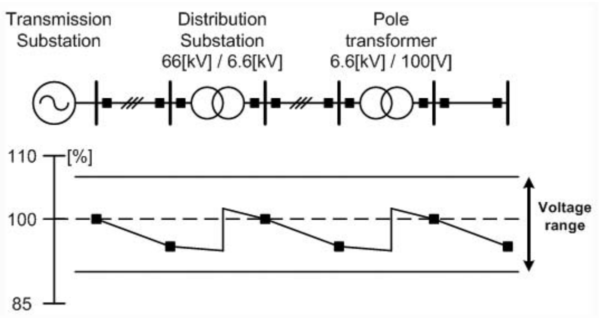


Fig. 1. The present power system.

However, when the clustered PV system connects with distribution system and reverse power flows, the distribution line voltage increases. The clustered PV system connected with distribution system is shown in Fig. 2.

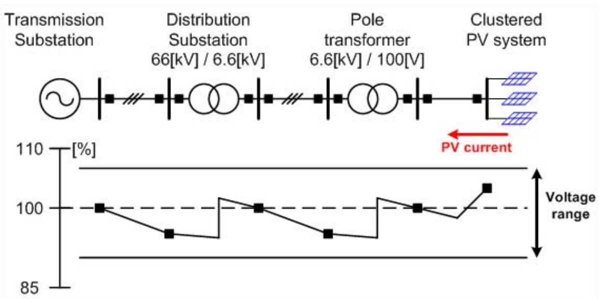


Fig. 2. Clustered PV system connected with distribution system.

So far, some distribution voltage controllers have been used in the distribution system. Dynamic voltage restorer (DVR) and uninterrupted power supply (UPS) systems have been researched and developed along the last decades. They are capable of compensating under-voltage and over-voltage conditions. However, they depend on devices in order to store energy, like large capacitors or battery bank. If the power increases, the size of the devices will increase [2].

This paper proposes D-UPFC in order to control under- and over-voltage conditions in the distribution system. D-UPFC consists of ac-ac converter and the transformer. The ac-ac converter uses four MOSFET switches, input and output LC filters. D-UPFC employs all pass filter and d-q transformation. D-UPFC does not need any energy storage components, such as large capacitor or inductor. Morever, D-UPFC does not use any rectifier circuit in order to convert ac power to ac power. However, it directly converts ac to ac conversion.

This paper begins by studying D-UPFC concept with clustered PV system. D-UPFC circuit analysis is performed. In the D-UPFC control, all pass filter and d-q transformation methods are used in order to control distrubution line voltage simultaneously. Switching patterns, which are considered power flow, reverse power flow, and inductive load conditions, are proved in the simulation. Under-voltage and over-voltage conditions are proved using simulation tool, which named PSIM ver. 6.1.

## D-UPFC CONCEPT

D-UPFC can control under-voltage condition, which can happen during heavy load or short-circuit. Also, it can control over-voltage condition, which can occur during reverse power flow from clustered PV system. D-UPFC can be located at the back of the pole transformer or any place in the distribution line. The overview of D-UPFC installation is shown in Fig. 3. The higher power flows from the substation to the clustered PV system through the pole transformer.

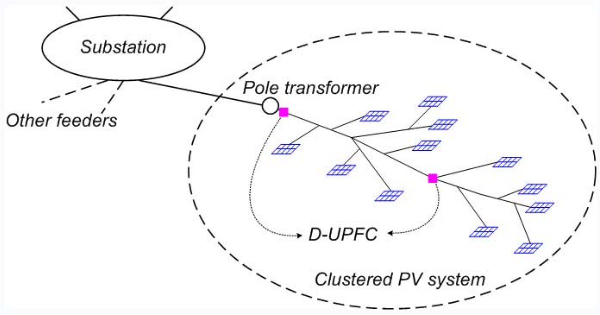


Fig. 3. Overview of D-UPFC installation.

## D-UPFC CIRCUIT ANALYSIS

AC-AC converter consists of four MOSFET switches, input and output LC filters. Its topology is the similar with dc-dc buck converter, but the difference is that it converts ac power to ac power. AC-AC converter output voltage can be expressed,

$$V_{load} = D \times V_s \quad (1)$$

Where, $V_s$ and $V_{load}$ are input and output voltage, respectively. $D$ is duty ratio.

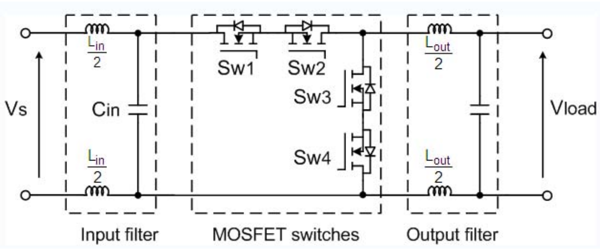


Fig. 4. AC-AC converter circuit.

Proposed D-UPFC topology is shown in Fig. 5. Here, the ac-ac converter controls distribution line voltage during under-voltage or over-voltage condition. D-UPFC output voltage is expressed,

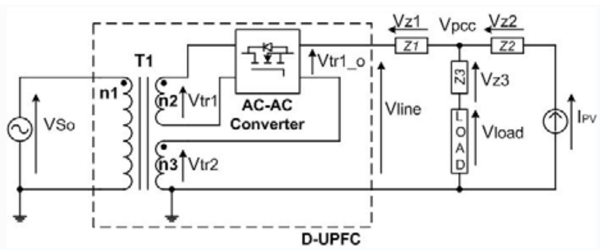


Fig. 5. Proposed D-UPFC topology.

$$V_{line} = \frac{n_2 + n_3}{n_1} \times V_{so} = V_{tr2} + V_{tr1\_o} = V_{tr2} + (D \times V_{tr1}) \quad (2)$$

Where, $n_1$ is the primary side and $n_2$, $n_3$ are secondary and tertiary sides of the transformer. $V_{so}$ is the source voltage and $V_{line}$ is distribution line voltage. $V_{tr1}$ and $V_{tr1\_o}$ are the secondary input and output voltage, respectively. $V_{tr2}$ is the tertiary voltage.

## D-UPFC SWITCHING PATTERN ANALYSIS

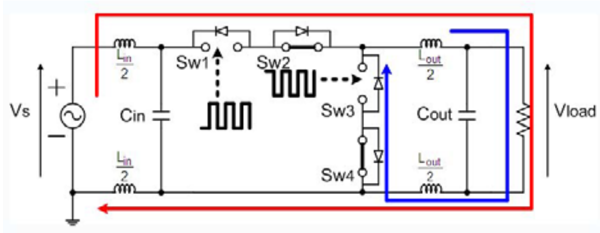


Fig. 6. AC-AC converter switching during power flow(Vs is plus polarity).

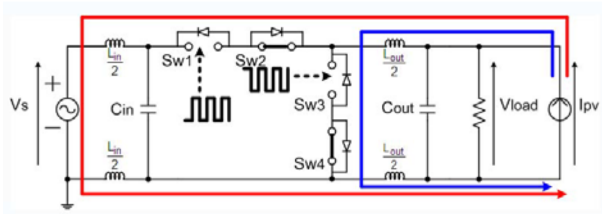


Fig. 7. AC-AC converter switching during reverse power flow(Ipv is plus polarity).

D-UPFC switching pattern can be considered in the three conditions. When the power flows from pole transformer to clustered PV system and Vs is plus polarity, ac-ac converter switches Sw1 and Sw3 are pwm and Sw2 and Sw4 are on. If Vs is minus polarity, Sw2 and Sw4 are pwm and Sw1 and Sw3 are on. Figure 6 shows the ac-ac converter switching pattern during power flow condition [3].

When the reverse power flow occurs from the clustered PV system to the distribution system and Ipv is plus polarity, Sw1 and Sw3 are pwm and Sw2 and Sw4 are on. If Ipv is minus polarity, Sw2 and Sw4 are pwm and Sw1 and Sw3 are on. Figure 7 shows the ac-ac converter switching pattern during reverse power flow condition [3].

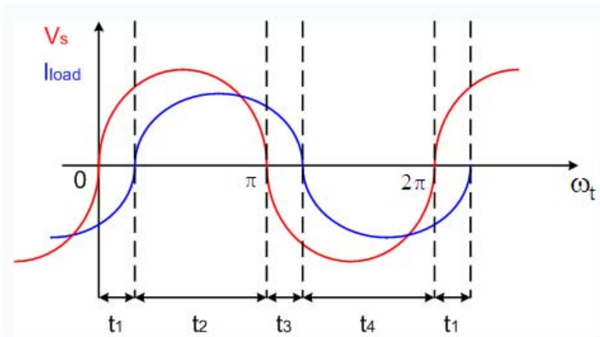


Fig. 8. Inductive load condition in the ac-ac converter.

When the inductive load connects with ac-ac converter, the output current is lag compared with input voltage. Thus, D-UPFC switching pattern should consider the phase condition. AC-AC converter source voltage $V_s$ and inductive output current $I_{load}$ can be shown in Fig. 8. In order to control the phase difference between $V_s$ and $I_{load}$, four periods of the switching pattern are shown in Table 1 [4].

Table 1. Switching pattern of inductive load.

| Period | Sw1 | Sw2 | Sw3 | Sw4 |
|---|---|---|---|---|
| $t_1$ | PWM | ON | PWM | ON |
| $t_2$ | PWM | ON | PWM | ON |
| $t_3$ | ON | PWM | ON | PWM |
| $t_4$ | ON | PWM | ON | PWM |

### D-UPFC CONTROL

All pass filter and d-q transformation are used in the D-UPFC control. The d-q transformation changes fundamental frequency signals to dc components, allowing a fast transient response to control distribution line voltage. The all pass filter shifts fundamental sine waveform(real value) to 90 degree lead or lag(imaginary value) in order to employ d-q transformation. Figure 9 shows the phase shift concept.

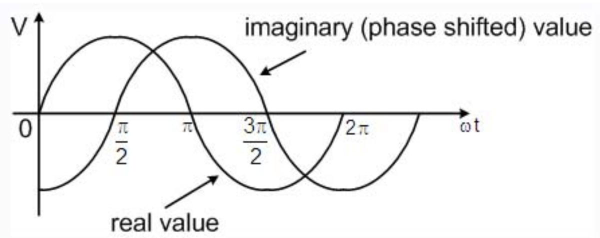


Fig. 9. Real and imaginary values in the all pass filter

Using the all pass filter concept, the real and imaginary values can be expressed,

$$V_r = b_1 sin(\omega t) \quad (3)$$

$$V_i = b_1 sin(\omega t - \frac{\pi}{2}) = -b_1 cos(\omega t) \quad (4)$$

Where, $V_r$ and $V_i$ mean real and imaginary values, respectively. $b_1$ is the instantaneous voltage magnitude. According to eq. (3) and (4), the single-phase d-q transformation is given by,

$$\mathbf{V}_{dq} = \mathbf{T}\mathbf{V}_{ri} \quad (5)$$

Where, $\mathbf{T} = \begin{bmatrix} sin\theta & -cos\theta \\ cos\theta & sin\theta \end{bmatrix}, \theta = \omega t$

Where, $V_d$ and $V_q$ indicate the real and imaginary voltages, respectively [5]. D-UPFC control block is shown in Fig. 10. The purpose of D-UPFC control is that D-UPFC output voltage $V_{load}$ always follows the reference voltage $V_{ref}$. D-UPFC input voltage $V_s$, output voltage $V_{load}$ and current $I_{load}$ are sensed and change the original values to dc values using all pass filter and d-q transformation functions. The voltage error $V_{error}$ is controlled using PI compensator and then it compares with carrier waveform in the PWM function. The final pwm signal inputs four switches considering phase angle between $V_s$ and $I_{load}$.

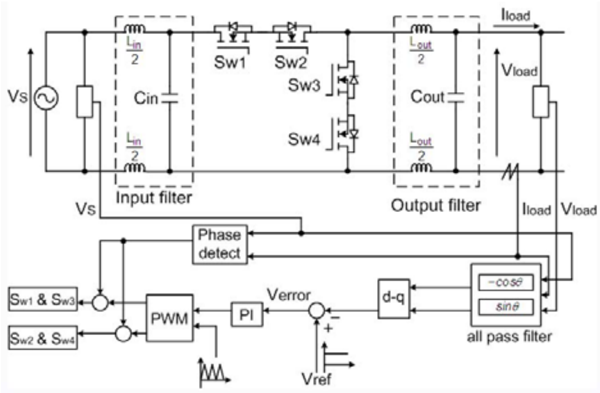


Fig. 10. D-UPFC control block.

### D-UPFC SIMULATION & EXPERIMENT

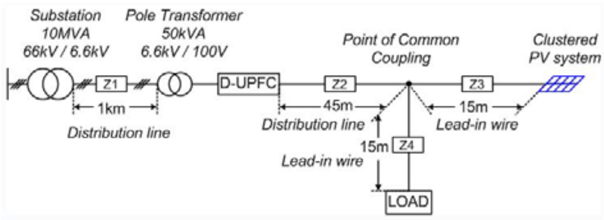


Fig. 11. D-UPFC simulation model.

D-UPFC simulation model is considered from the substation to the load and clustered PV system. The basic simulation model is shown in Fig. 11. D-UPFC locates behind the pole transformer. Considering line impedances in the distribution system, the distance between the substation and the pole transformer is 1[km], rom D-UPFC to the point of common coupling (PCC) is 45[m]. The distance between PCC and the load or clustered PV system is 15[m].

D-UPFC simulation model parameters are shown in Table 2. Also, ac-ac converter parameters are shown in Table 3.

Table 2. D-UPFC simulation model parameters.

| | |
|---|---|
| Substation vol.(sec.) | 6.6[kV, rms] |
| Pole trans. vol.(sec.) | 100[V,rms] |
| $Z_1$ | 0.025+j0.034[Ω/1km] |
| $Z_2$ | 0.011+j0.013[Ω/45m] |
| $Z_3$ & $Z_4$ | 0.00345+j0.00015[Ω/15m] |
| Load | 3.33[Ω] |
| $I_{pv}$ | 100[A,rms] |
| Max. output voltage | 100[V,rms] |
| Max. output current | 70[A,rms] |
| Max. power | 7[kW] |

Table 3. AC-AC converter parameters.

| | |
|---|---|
| Max. output voltage | 10[V,rms] |
| Max. output current | 70[A,rms] |
| Max. power | 700[W] |
| Input & Output L and C | 176.75[μH], 15.94[μF] |

Figure 12 shows the experimental result of the ac-ac converter switching pattern. The switching pattern $S_{w1}$ depends on the source voltage $V_s$.

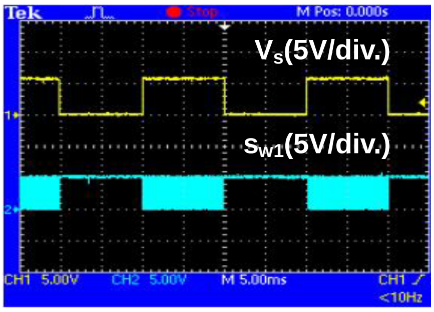


Fig. 12. AC-AC converter switching pattern.

The under-voltage simulation result is shown in Fig. 13. Here, D-UPFC control voltage is expressed,

$$V_{ref} - V_s > 2[V, rms] \quad (6)$$

Where, $V_{ref}$ shows the D-UPFC reference voltage. In the simulation, D-UPFC refecence voltage $V_{ref}$ is fixed to 101[V,rms]. The source voltage $V_s$ changes 98[V,rms] to 93[V,rms], because the under-voltage affects the source voltage from 2[V,rms] to 6[V,rms]. $V_{line}$ shows distribution line voltage and it is affected by under-voltage condition. $V_{line\text{-}controlled}$ means D-UPFC controlling voltage. $V_{line\text{-}controlled}$ is changed 100.4[V,rms] to 99.1[V,rms] when D-UPFC performed.

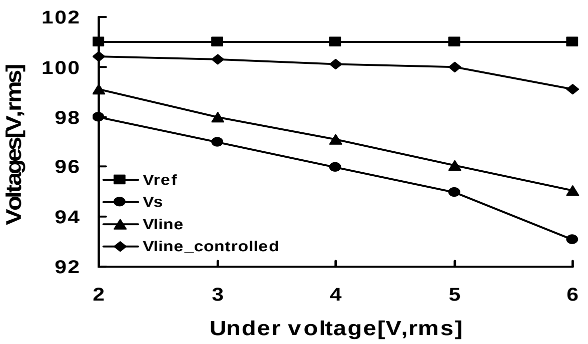


Fig. 13. D-UPFC control in the under-voltage condition.

The over-voltage simulation result is shown in Fig. 14. Here, D-UPFC control voltage expresses,

$$V_{line} - V_{ref} > 2[V, rms] \quad (7)$$

Where, $V_{line}$ means the distribution line voltage. In the simulation, reverse power from clustered PV system flows from 70[A,rms] to 100[A,rms]. $V_{ref}$ is the D-UPFC reference voltage. When the $I_{pv}$ changes 70[A] to 100[A], $V_{line}$ also changes 104.3[V,rms] to 107.2[V,rms]. D-UPFC controls voltage 102.2[V,rms] to 103.7[V,rms] during over-voltage condition.

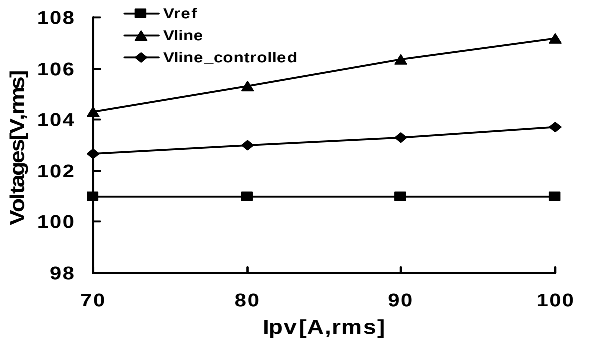


Fig. 14. D-UPFC control in the over-voltage condition.

## CONCLUSION

Proposed D-UPFC is shown in this paper. D-UPFC controlled the distribution line voltage during under- and over-voltage conditions. D-UPFC concept, circuit, switching pattern, and control method are analyzed. The proposed D-UPFC proves the performance using simulation and experimental results. However, it needs more reliability tests during reverse power flow condition.

## ACKNOWLEDGEMENT

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