Voltage Regulation in Distribution System using the Combined DVR

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***Abstract*- In recent years, renewable energy system such as Photovoltaic generation system (PV) is widely introduced in distribution system. On the other hand, voltage deviation due to voltage fluctuation and unbalanced voltage caused by PV becomes serious problem. In order to mitigate those problems, the Combined type Dynamic Voltage Regulator (C-DVR) which consists of a step voltage regulator and AC chopper is the effective device. C-DVR can regulate line voltage continuously and quickly. This paper shows the effectiveness of C-DVR by the numerical simulation.**

Keywords— Dynamic voltage regulator, AC chopper, Voltage control, Photovoltaic generation system.

I. Introduction

In recent years, Dispersed Energy Generation systems (DEG) such as Photovoltaic generation system (PVs), Fuel Cell generation (FC) are widely introduced in power systems. Especially, a roof top type PV and FC are attracted and installed in many residential house in Japan, therefore most of DEG are connected via single phase Power Conditioning System (PCS). The much of the unbalanced current flows in a distribution line, therefore the unbalanced voltage may become larger. On the other hand, most of distribution systems are radial system and the voltage of distribution line is controlled by Load Ratio control Transformer (LRT) in a substation (S/S) and Step Voltage Regulator (SVR) in a line and pole transformer to keep within adequate range (Fig.1). Since LRT and SVR are one of a transformer which control the voltage automatically by changing winding ratio, the voltage can be varied discretely and non-phase segregated change. Therefore, the unbalanced voltage in distribution system cannot be regulated by those devices. Furthermore, the output of PV fluctuates frequently and violently depending on weather conditions, amount of unbalanced voltage also may vary frequently and randomly. As a result, single-phase PV system may cause one or two phase voltage deviation from the proper range frequently. However, LRT and SVR has slow speed mechanical operation, and it cannot regulate the voltage effectively. Furthermore, frequently operation of SVR may lead to deterioration of contact for attrition.

In previous research, high speed voltage regulation devices such as Static Var Compensator (SVC), Unified Power Flow Controller (UPFC), are proposed. However, those devices are expensive and it is difficult to install on the distribution line. Thyristor type Step Voltage Regulator (TVR) is also proposed as a faster voltage regulation device, but it cannot regulate the voltage continuously.

From this background, this paper proposes the novel voltage regulator so called the Combined type Dynamic Voltage Regulator (C-DVR). C-DVR consists of a step voltage regulator by thyristor devices (TVR configuration) and AC chopper by IGBT devices and regulates the voltage by injecting the compensating voltage in series to the distribution line. Hence, only the small capacity of AC chopper is combined to TVR configuration, and the cost could be reduced. In this paper, the effectiveness of C-DVR in terms of the suppression of voltage fluctuation due to PV and the reduction of the unbalanced voltage is presented. The configuration of C-DVR is described in detail in Chapter 2. In Chapter 3 the control scheme of the unbalanced voltage compensation is explained. Simulation results are shown in Chapter 4.

II. Configuration of C-DVR

1. Dynamic voltage regulator

C-DVR consists of TVR configuration and AC chopper, regulates the voltage by injecting the compensating voltage in series to the distribution line (Fig. 2). v_{si} ($i=u,v,w$) is source voltage, R and L are resistance and inductance of the distribution line. v_{fi}($i=u,v,w$) is the compensating voltage produced by C-DVR. v_s is the voltage at the source side, and the v_l is the load side voltage.

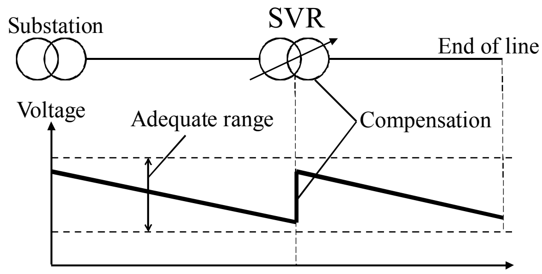


Fig.1 Radial distribution system

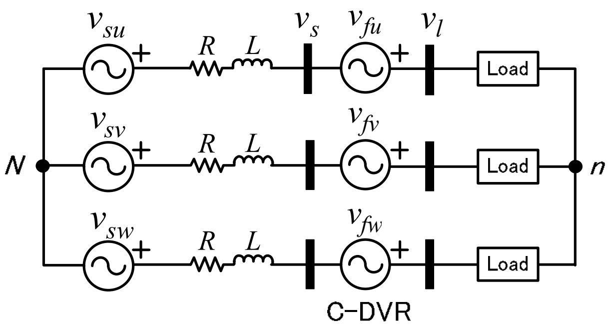


Fig. 2 Schematic diagram of a DVR

2. Combined AC Choppers

C-DVR for three phase line consists of two Combined AC Choppers (CACCs). Fig. 3 shows the configuration of CACC. CACC is a back-boost AC chopper and consists of five bidirectional GTOs (Th0~ Th4) and two bidirectional IGBTs. It has also L-C filters that consist of L_f and C_f in input side and consist of L_o and C_o in output side. GTOs (Th_1 ~ Th_4) are used for discrete voltage regulation in four levels (V_{in}, $0.5V_{in}$, $-0.5V_{in}$, $-V_{in}$) shown in Fig. 4. When it outputs the zero voltage, Th_0 is turned ON. After the discrete voltage regulation by GTOs, AC chopper regulate the output voltage precisely by controlling the duty ratio D in the each range of V_{RANGE} (V_{PH}, V_{PL}, V_{NH} and V_{NL}).

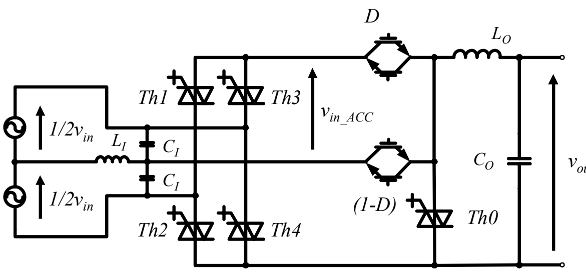


Fig.3 The construction of CACC

Fig. 5 shows current flow diagrams in the each range of V_{RANGE}. v_{out} of the case of V_{PH} (V_{PH} mode) is represented by Eq. (1)

<V_{PH} mode: $0.5V_{in} \le V_{in\_ACC} \le V_{in}$>

$$v_{out} = \frac{(1+D)}{2} \cdot V_{in} \sin(\omega t) \qquad (1)$$

In Fig. 5 (a), solid or dotted line shows the change of current flow by switching of the IGBT. Thus HACC can output positive and negative voltage continuously in the range from V_{in}~$0.5V_{in}$.

The control scheme of the other mode is same as V_{PH} mode.

<V_{PL} mode: $0 \le V_{in\_ACC} \le 0.5V_{in}$>

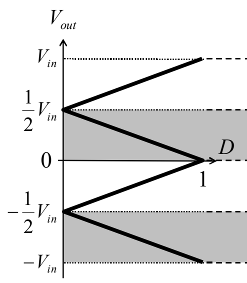
$$v_{out} = \frac{(1-D)}{2} \cdot V_{in} \sin(\omega t) \qquad (2)$$

<V_{NH} mode: $-0.5V_{in} \le V_{in\_ACC} \le 0$>

$$v_{out} = -\frac{(1-D)}{2} \cdot V_{in} \sin(\omega t) \qquad (3)$$

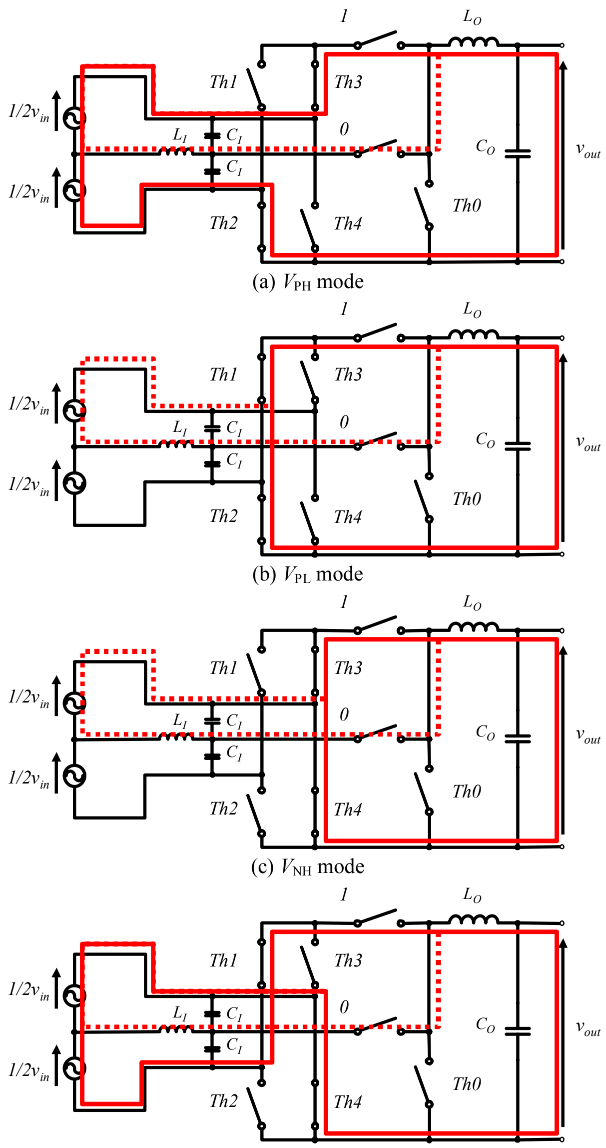
<V_{NL} mode: $-V_{in} \le V_{in\_ACC} \le -0.5V_{in}$>

$$v_{out} = -\frac{(1+D)}{2} \cdot V_{in} \sin(\omega t) \qquad (4)$$



V_{RANGE}	Th1	Th2	Th3	Th4
V_{PH}	ON	OFF	OFF	ON
V_{PL}	OFF	OFF	ON	ON
V_{NH}	ON	ON	OFF	OFF
V_{NL}	OFF	ON	ON	OFF

Fig.4 The output of CACC



(d) V_{NL} mode

Fig.5 The detail of method to output voltage by CACC

From eq. (1) to eq. (4), V_{in} is determined by Eq. (5) and C-DVR is possible to control the output voltage by determining the coefficient K.

$$v_{out} = K \cdot v_{in} \quad (-1 \le K < 1) \qquad (5)$$

Thus, since the voltage applied to the IGBT is half of V_{in}, the capacity of IGBT is small and the cost of CACC may become lower. Furthermore, switching frequency of the small capacity of IGBTs can be high, hence the response of C-DVR can be more quickly.

3. Configuration of C-DVR

The configuration of C-DVR is shown in Fig. 6. V_L stands for the voltage at the load side, and V_S stands for the voltage of the source side. In order to control the three phase voltage, C-DVR has two CACCs. The input voltage of each CACC is provided via the parallel connected transformer from the distribution line and the output voltage of CACC is applied to the distribution line via a series transformer. To reduce the number of switches, two CACCs are connected by V connection.

As described in the last section, CACC can regulate the voltage continuously and quickly, C-DVR can suppress the voltage fluctuation precisely. Therefore the violent voltage fluctuation caused by large amount of PVs can be compensated using C-DVR.

The reference voltage V_{ref} is determined according to the conditions of the distribution line. Then the difference between V_L and V_{ref} is calculated and the compensation voltage which is the output of CACC is determined by conversion from line voltage to phase voltage. Thus, the load voltage can be regulated at constant value.

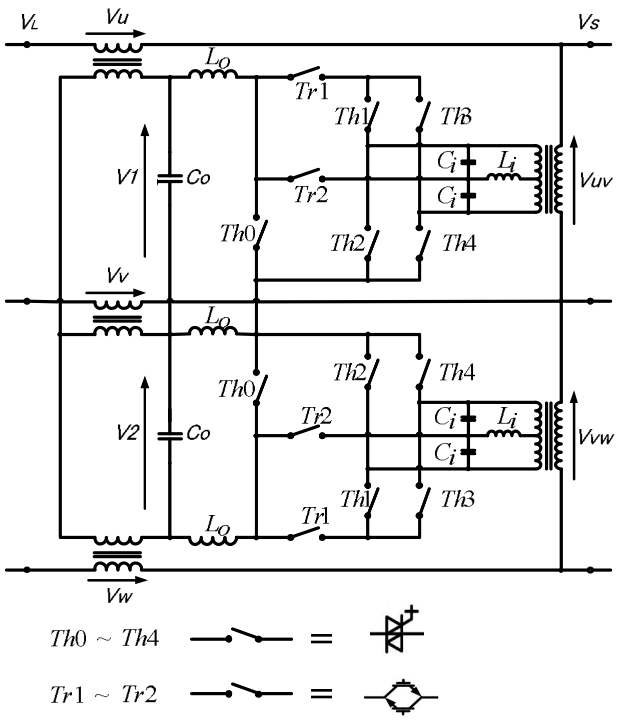


Fig. 6 The configuration of C-DVR

III. Unbalanced voltage compensation by C-DVR

When the large amount of residential PVs is connected to the line in single phase, the problem of unbalanced voltage may become more seriously. The unbalanced voltage causes the problems to an induction motor, such as increasing the loss and torque fluctuation. Furthermore, the control of the voltage in the distribution line by utility company may become more difficult. Therefore, the suppression of unbalanced voltage is very important issue in terms of power quality.

In order to reduce the unbalanced voltage, C-DVR should output the negative phase sequence component of the line voltage. Therefore, the magnitude and phase angle of output voltage should be controlled by the input voltage V_{in} that is the line voltage at the source voltage V_S.

To achieve this aim, the output voltage of CACC is modulated by second harmonic.

The input voltage v_{in} is expressed in Eq. (6).

$$v_{in} = V_{in}\sin(\omega t + \varphi_{in}) \tag{6}$$

V_{in}: Amplitude of input voltage

φ_{in} : Phase angle

The reference of the output voltage of CACC v_1 is determined by the modulating coefficient K which is given in Eq. (7).

$$v_1 = K \cdot v_{in}$$
$$K = K_0 + K_2\sin(\omega t + 2\varphi_{in}) \tag{7}$$

K_0: Basic coefficient

K_2: Second harmonic coefficient

Then the output voltage v_1 is expressed in Eq. (8) [3].

$$\begin{aligned} v_1 &= K \cdot v_{in} \\ &= V_{in}\sqrt{{K_0}^2 + \left(\frac{K_2}{2}\right)^2}\sin(\omega t + \varphi_{in} + \varphi) \\ &\quad - \frac{K_2 V_{in}}{2}\cos(3\omega t + 3\varphi_{in}) \end{aligned} \tag{8}$$

Where, $\varphi = \tan^{-1}\frac{K_2}{2K_0}$.

From Eq. (8), the amplitude and phase angle of the output voltage can be controlled by changing K_0 and K_2. Although third harmonic voltage is appeared in the output voltage, it may be small enough for the unbalanced voltage compensation. K_0 and K_2 is determined as follows.

The relation between the output of C-DVR and that of CACCs is represented in Eq. (9).

$$\begin{cases} v_1 = v_u - v_v \\ v_2 = v_v - v_w \end{cases} \tag{9}$$

v_1: Output voltage of CACC1 (Upper side)

v_2: Output voltage of CACC2 (Lower side)

The reference of the output voltage of C-DVR is defined in Eq. (10) using the reference value of the positive-phase- sequence voltage V_p^* and the negative-phase-sequence voltage V_n^* .

$$\begin{cases} v_u^* = V_p^* \sin(\omega t + \varphi_p) + V_n^* \sin(\omega t + \varphi_n) \\ v_v^* = V_p^* \sin(\omega t + \varphi_p - 2/3\pi) + V_n^* \sin(\omega t + \varphi_n - 2/3\pi) \\ v_w^* = V_p^* \sin(\omega t + \varphi_p + 2/3\pi) + V_n^* \sin(\omega t + \varphi_n + 2/3\pi) \end{cases} \quad (10)$$

Then the output of CACCs is determined by Eq. (11) from Eq.(9).

$$\begin{cases} v_1 = v_u^* - v_v^* \\ \quad = \sqrt{(A-C)^2 + (B-D)^2} \sin(\omega t + \tan^{-1}\dfrac{B-D}{A-C}) \\ v_2 = 2v_v^* + v_w^* \\ \quad = \sqrt{(2A+C)^2 + (2B+D)^2} \sin(\omega t + \tan^{-1}\dfrac{2B+D}{2A+C}) \end{cases}$$

$$\begin{aligned} A &= V_p \cos\varphi_p + V_n \cos\varphi_n \\ B &= V_p \sin\varphi_p + V_n \sin\varphi_n \\ C &= V_p \cos(\varphi_p - 2/3\pi) + V_n \cos(\varphi_n - 2/3\pi) \\ D &= V_p \sin(\varphi_p - 2/3\pi) + V_n \sin(\varphi_n - 2/3\pi) \end{aligned} \quad (11)$$

The reference value of the positive-phase- sequence voltage V_p^* is determined according to the conditions of the distribution line and the negative-phase- sequence voltage V_n^* is zero in order to suppress the unbalanced voltage. Thus, the coefficient K_0 and K_2 is determined by using Eq. (8) and Eq. (11).

IV. SIMULATION

1. Suppression of the voltage fluctuation

In order to confirm the effectiveness of the C-DVR, the numerical simulation using MATLAB/Simulink is performed. The distribution model is shown in Fig. 7. The large amount of PV (MEGA Solar) is connected at the end of line. The maximum output of PV is 4[MW] and the output of PV is fluctuated as shown in Fig. 8 which is modified form the actual data. C-DVR is installed around the center of the line. The capacity of C-DVR is 180[kVA] that is determined to be able to control the line voltage ±300 [V] in the steady state. The loads connected in each load is set as R-L load and its capacity is 125[kVA] and power factor is 0.98(lagging). The other simulation conditions are shown in Table 1. The specification of C-DVR is shown in Table 2.

The maximum output voltage V_{out_MAX} at the series transformer of C-DVR is restricted by the line voltage of distribution line. When the effective value of the phase voltage at point A is V_i ($i = u, v, w$), the maximum output voltage of C-DVR is restricted by Eq. (9) using the winding ratio of the shunt transformer and series transformer.

$$V_{out\_MAX} = V_i \times \frac{2000}{6600} \times \frac{100}{500} \quad (9)$$

The output voltage of each CACC is regulated using the modulating coefficient K from Eq. (5). In order to suppress the voltage fluctuation caused by PV, K is determined by Eq. (10).

$$K = \frac{V_i - V_{ref}}{V_i \times 2000/6600 \times 100/500} \quad (10)$$

where, V_i : the phase voltage at the point A

V_{ref} : the reference voltage

The reference voltage V_{ref} is determined in considering of the conditions of a distribution line. In this simulation, the reference voltage V_{ref} is set 6340[V] in considering the voltage drop of the distribution line in case of that the PV is not connected.

The simulation results are shown in Fig. 9. Although the voltage at the point A fluctuates due to the output fluctuation of PV, the voltage at the point B is sufficiently suppressed by using C-DVR.

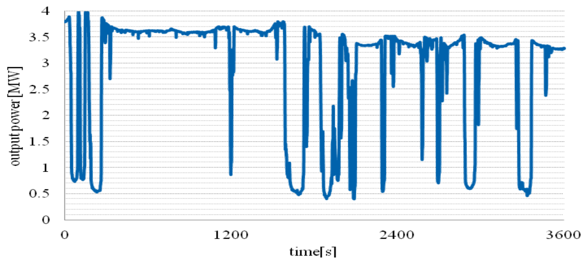


Fig. 8 The output of PV

Table 1
Simulation Conditions

		Value	
Sending voltage of S/S		6600 [V]	
Line impedance		R	0.139 [Ω]
		L	0.4 [mH]
Load	Capacity	125	[kVA]
	Power factor	0.98	(Lagging)
	impedance	R	118.5 [Ω]
		L	583.7 [H]

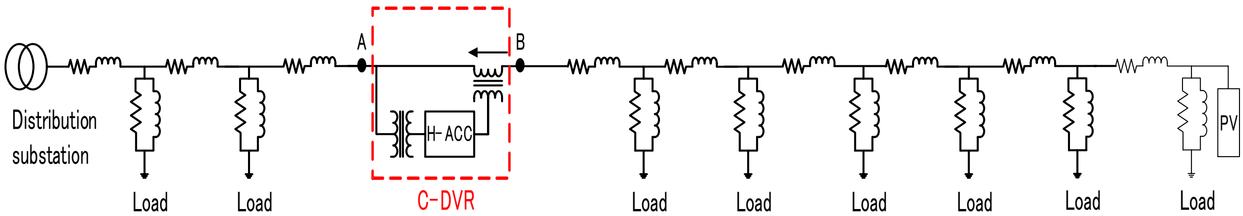
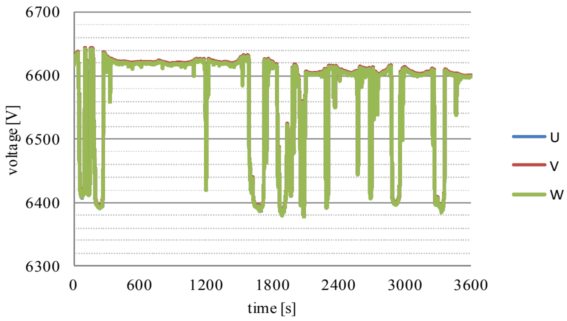


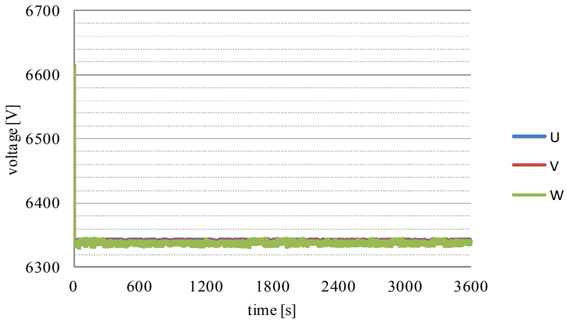
Fig. 7 Simulation model of suppression of voltage fluctuation

Table 2
Specification of C-DVR

	Value	
Controllable Voltage Range	± 300[V]	
Winding ratio of shunt transformer	2000/6600 [V]	
Winding ratio of series transformer ratio	100/500 [V]	
GTO turn on time	0.05 [ms]	
Input filter	L_i	0.5 [mH]
	C_i	0.05 [mF]
Output filter	L_i	2.0 [mH]
	C_i	0.01 [mF]
Total AC chopper capacity	90 [kVA]	



(a) Voltage at point A



(b) Voltage at point B
Fig. 9 Simulation result of suppression of voltage fluctuation

2. Reduction of the unbalanced voltage

In order to clear the effectiveness of the unbalanced voltage suppression, PV is not considered in this simulation. The simulation model is shown in Fig. 8. In this model, the sending voltage at the distribution substation (S/S) is unbalanced. The amplitude of the positive-phase-sequence component of the sending voltage is set $6600\sqrt{2/3}$ [V] and the negative-phase-sequence component of it is set 100[V] respectively. In this case, the voltage unbalance rate is 1.85%.

The modulating coefficient K_0 and K_2 in Eq.(8) is determined from that the the negative-phase-sequence component of the voltage is zero.

Simulation result of the voltage at the point B is shown in Fig. 9. C-DVR starts the compensation at 0.05[s]. After the suppression of the negative phase sequence component by C-DVR, the unbalanced voltage at the point B is reduced sufficiently and stably. The voltage unbalance rate at the point B becomes 0.08%.

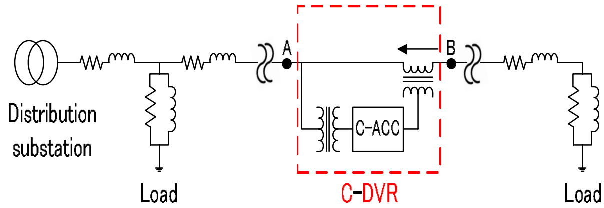


Fig. 8 Simulation model of unbalanced line voltage

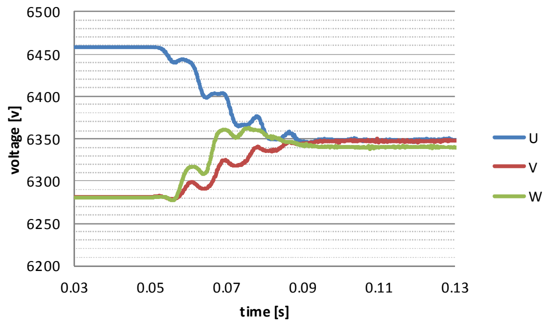


Fig. 9 Simulation result of reduction of unbalanced voltage

V. Conclusion

In this paper, the novel voltage regulator C-DVR is proposed. C-DVR consists of a step voltage regulator by thyristor devices (TVR configuration) and AC chopper by IGBT devices and regulates the voltage by injecting the compensating voltage in series to the distribution line. The feature of C-DVR is fast and continuous regulation of the distribution line and the lower cost as compared with SVC or UPFC.

By the numerical simulation using the distribution model, it is confirmed that C-DVR is able to suppress the voltage fluctuation caused by PV sufficiently.

Furthermore, the control scheme of the unbalanced voltage suppression is also presented, and the unbalanced voltage in the sending voltage at the S/S is reduced at the point of the load side by using C-DVR.

However, the third harmonics is remained in the voltage according to the second harmonic modulation. Therefore, in case of the large negative-phase-component of the voltage compensation, the third harmonic voltage may affects to the distribution line. The reduction method of the third harmonic voltage is the future works. And the experimental verification using a prototype model is also the next challenge.

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