Application of Electric Double Layer Capacitor to Single-Phase Composite PWM Voltage Source Inverter

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Keywords: composite PWM, voltage source inverter, PV system, EDLC

This paper proposes an application of electric double layer capacitor (EDLC) to single-phase composite PWM voltage source inverter (VSI).

Fig. 1 shows a PV system which consists of the single-phase composite PWM VSI. The VSI consist of the normal single-phase bridge circuit and an additional arm. The two auxiliary self-turn-off devices of the arm avail to adopt a composite PWM control, which contributes to reduce the ripple in the ac output current. Fig. 1(a) shows in the dc side, the dc current contains the ac component, which has twice the system frequency. Until now, LC series resonance circuit tuned to twice the utility frequency is necessary to connect to the smoothing capacitor in parallel. Hence, the smoothing capacitor is drastically reduced. The VSI is disadvantageous in maintenance to use storage battery in order to stabilize the dc voltage.

Fig. 1(b) shows the adoption of EDLC to smoothing capacitor in the dc side of the PWM VSI. The EDLC absorbs the ac component with twice the utility frequency and the ripple caused by PWM switching included the dc pulsating current. The smooth dc current is obtained by using the EDLC.

An equipment of VSI type made on an experimental basis. Design parameters of the parts were $L_{f1} = L_{f2} = 0.75$ mH, $C_f = 20$ μ F, $L_s = 6.12$ mH, $C_d = 220$ μ F, $C'_d = 440$ μ F, $L_d = 3.25$ mH, EDLC = 0.62 F, respectively.

Fig. 1. Utility interactive PV system with single-phase composite PWM VSI

Fig. 2 gives the experimental waveforms of the voltage and the current when $\alpha = 25^\circ$, $MI = 0.93$, $E_d = 157$ V, $I_d = 8.4$ A, $E_u = 86$ V, $I_u = 14$ A, $p.f. = 1$.

In this paper, the VSI circuit configuration, the principle of the composite PWM methods and measured by experiment are described. The experiments prove that the smooth dc current is obtained by using the EDLC. This paper also shows the composite PWM strategy with two types of the patterns contributes to reduce the ripple of the current.

Fig. 2. Experimental waveform ($\alpha = 25^\circ$, $MI = 0.93$, $E_d = 157$ V, $I_d = 8.4$ A, $p.f. = 1$, $E_u = 86$ V, $I_u = 14$ A)

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This paper proposes an application of electric double layer capacitor (EDLC) to single-phase composite PWM voltage source inverter (VSI). The VSI consist of the normal single-phase bridge circuit and an additional arm. The two auxiliary self-turn-off devices of the arm avail to adopt a composite PWM control, which contributes to reduce the ripple in the ac output current. In the dc side, the dc current contains the ac component, which has twice the system frequency. Until now, LC series resonance circuit tuned to twice the utility frequency is necessary to connect to the smoothing capacitor in parallel. Hence, the smoothing capacitor is drastically reduced. The VSI is disadvantageous in maintenance to use storage battery in order to stabilize the dc voltage.

This paper describes an application of EDLC to smoothing capacitor in the dc side of the PWM VSI. The EDLC absorbs the ac component with twice the utility frequency and the ripple caused by PWM switching included the dc pulsating current. The smooth dc current is obtained by using the EDLC.

The experiment shows that the single-phase composite PWM VSI used for the utility connected residential photovoltaic power generation system (PV system).

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1. Introduction

The single-phase composite PWM VSI circuit was invented by Nonaka⁽¹⁾⁽²⁾. The utility interactive PV system⁽³⁾⁽⁴⁾ is equipped with PV array, battery storage and the single-phase VSI which has an additional arm to normal single-phase bridge circuit. The VSI provides a sine wave output current for domestic loads and the utility when the PV array's output exceeds the load demand. A storage battery is added to PV array in parallel in order to stabilize dc voltage. The VSI output current is controlled by both of the firing angle α and the modulation index MI ⁽⁵⁾⁻⁽⁸⁾.

The instantaneous ac power will pulsate at twice the ac frequency in a single-phase circuit, very large dc capacitor is required. The authors have greatly decreased the capacity of the capacitor by applying the LC series resonance circuit⁽¹⁾⁻⁽⁴⁾. However, when the reactor is used, weight becomes heavy. The authors proposed an application of EDLC to smoothing capacitor.

In this paper, the experimental results using 1 kVA trial single-phase composite PWM VSI adapted the utility connected residential photovoltaic power generation system (PV system) are shown.

2. Circuit Configuration

Fig. 1 shows a PV system which consists of the single-phase composite PWM VSI. The VSI circuit is composed of the usual single-phase bridge circuit consisting of four main IGBTs $S_1 \sim S_4$ and additional arm of IGBT's S_5 and S_6 with

antiparallel diodes respectively. The ac filter reactor is divided L_{f1} and L_{f2} , which flow a-half of output current in parallel, respectively. L_s indicate the interconnected reactor between the PV system and the utility. A storage battery is added on the dc side in order to stabilize dc voltage.

Fig.1(a) shows in the dc side, LC double-frequency series resonance circuit is connected in parallel to the dc capacitor. The dc current i_d contains the ac component which has twice the system frequency. When the parameters L_d and C_d' of the resonance circuit are satisfied with the following relation:

Fig. 1. Utility interactive PV system with single-phase composite PWM VSI

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$$2\omega L_d = 1/(2\omega C_d') \dots \dots \dots (1)$$

Hence, the impedance of the series resonance circuit becomes zero for the ac component of the current i_d . The smoothing capacitor C_d operates only as a bypass capacitor of the ripple current due to PWM switching, and is a capacitance small enough to absorb the ripple.

Fig. 1(b) shows the adoption of EDLC for smoothing capacitor. EDLC (2.3 V, 56F) with the parallel monitor⁽⁹⁾ is connected 90 in series. The EDLC absorbs the ac component with twice the utility frequency and the ripple caused by PWM switching included the dc pulsating current.

3. Composite PWM method

Fig. 2 shows composite PWM method⁽¹⁾⁽²⁾, which is accomplished by means of two type of PWM patterns produced by using a sinusoidal modulating wave ξ and two triangular carrier waves e_{s1} and e_{s2} .

In the main IGBTs S_1 and S_3 on the same arm, ON/OFF are repeated alternatively by the PWM patterns determined at the intersecting point of the triangular carrier wave e_{s1} and the sinusoidal modulating wave ξ .

In the main IGBTs S_4 and S_2 on the other arm, ON/OFF are repeated alternatively by each half-cycle.

On the other hand, in auxiliary IGBTs S_5 and S_6 , ON/OFF are repeated alternatively at the intersecting point of the reverse-phase triangular carrier wave e_{s2} and ξ .

The modulation index MI is defined as follows,

$$MI = \frac{\text{Amplitude of the sinusoidal modulating wave}}{\text{Amplitude of the triangular carrier wave}} \dots \dots \dots (2)$$

where, $0 \leq MI < 1$. The modulation index MI can be changed by varying the amplitude of the modulating wave ξ while keeping that of the carrier wave e_{s1} and e_{s2} .

4. Operating modes

Fig. 3 shows example of the operating modes in the period $\alpha \leq \omega t \leq \pi$, that is $e_{su} > 0$, $e_u > 0$, $i_u > 0$.

(a) mode 1 shows the case of that i'_{u1} is supplied through S_1 and S_4 , i'_{u2} is circulating through D_6 and S_4 .

(b) mode 2: i'_{u1} is supplied through S_1 and S_4 , i'_{u2} also is supplied through S_5 and S_4 .

(c) mode 3: i'_{u1} is circulating through D_3 and S_4 , i'_{u2} is supplied through S_5 and S_4 .

(d) mode 4: i'_{u1} and i'_{u2} are circulating through D_3 and S_4 , and D_6 and S_4 , respectively.

5. Current control method

Fig. 4 shows control method of ac output current i_u by the phasor diagram. Fig. 4(a) gives the firing angle α control and fixed MI at $E_{su} = E_u$. Fig. 4(b) shows α and MI control to keep power factor at unity.

In VSI, the sinusoidal modulating wave ξ can be expressed by the following equation,

$$\xi = MI \sin \omega t \dots \dots \dots (3)$$

The inverter output voltage becomes

$$\begin{aligned} e_{su} &= E_d \cdot \xi \\ &= E_d \cdot MI \sin \omega t \\ &= \sqrt{2} E_{su} \sin \omega t \dots \dots \dots (4) \end{aligned}$$

Therefore,

Fig. 2. Composite PWM method

Fig. 3. Example of operating mode

$$E_{su}/E_d = MI/\sqrt{2} \dots \dots \dots (5)$$

When the MI is fixed at $E_{su} = E_u$,

$$e_u = \sqrt{2}E_u \sin(\omega t - \alpha) \dots \dots \dots (6)$$

$$E_d = \sqrt{2}E_u/MI \dots \dots \dots (7)$$

This means that E_d must be selected larger than the peak voltage of the utility line. The ac output current i_u will be obtained from the following

$$(L_s + L_f/2) \frac{di_u}{dt} = e_{su} - e_u$$

$$= \sqrt{2}E_u \{\sin \omega t - \sin(\omega t - \alpha)\} \dots \dots (8)$$

$$i_u = \sqrt{2}I_u \sin(\omega t - \alpha/2) \dots \dots \dots (9)$$

The effective value of i_u :

 (a) α control and fixed MI at $E_{su} = E_u$

 (b) α and MI control to keep power factor at unity

Fig. 4. Current control method

 Fig. 5. Relation between MI and α at the unity power factor control

$$I_u = \frac{2E_u}{X_s} \sin \frac{\alpha}{2} \dots \dots \dots (10)$$

where, $X_s = \omega(L_s + L_f/2)$

The mean value of the pulsating dc current i'_d is given by

$$i'_d = i_u \cdot \xi$$

$$= I_d - (MI \cdot I_u / \sqrt{2}) \cos(2\omega t - \alpha/2) \dots \dots \dots (11)$$

$$I_d = (MI \cdot I_u / \sqrt{2}) \cos \frac{\alpha}{2} \dots \dots \dots (12)$$

As shown in Fig. 4(b), the relations of α and MI to keep power factor at unity are given as follows,

(i) If E_d is assumed to be constant.

$$E_{su} = E_d MI / \sqrt{2} \dots \dots \dots (13)$$

Fig. 6. Experimental waveform ($\alpha = 25^\circ$, $MI = 0.93$, $E_d = 157$ V, $I_d = 8.4$ A, $p.f. = 1$, $E_u = 86$ V, $I_u = 14$ A)

Table 1. Design parameters of trial VSI

Part	Parameter
$S_1 \sim S_6$	MITSUBISHI Intelligent power module (PM75RSA060)
L_s	6.12 mH
C_f	20 μ F
$L_{f1} = L_{f2}$	0.75 mH
L_d	4.00 mH
C_d'	440 μ F
C_d	220 μ F
C_d (EDLC)	0.62 F

$$E_{su} \cos \alpha = E_u \dots\dots\dots (14)$$

$$E_{su} \sin \alpha = X_s I_u \dots\dots\dots (15)$$

At no-load $\alpha = 0$, $I_u = 0$

$$(E_{su})_{\alpha=0} = E_u = E_d(MI)_{\alpha=0} / \sqrt{2} \dots\dots\dots (16)$$

$$\therefore MI = (MI)_{\alpha=0} / \cos \alpha \dots\dots\dots (17)$$

Then,

$$I_u = (E_u / X_s) \tan \alpha \dots\dots\dots (18)$$

(ii) If the change of E_d caused by battery resistance R_b . MI has to be controlled according to the following relation,

$$E_d = (E_d)_{\alpha=0} - R_b I_d \dots\dots\dots (19)$$

$$\therefore MI = \frac{\frac{\cos \alpha}{(MI)_{\alpha=0}} - \sqrt{\left(\frac{\cos \alpha}{(MI)_{\alpha=0}}\right)^2 - \frac{R_b}{X_s} \sin 2\alpha}}{\frac{R_b}{2X_s} \sin 2\alpha} \dots\dots\dots (20)$$

Fig. 5 shows the relation between MI and α at the unity power factor control, under the condition of $f = 60$ Hz, $E_u = 100$ V, $(E_d)_{\alpha=0} = 177$ V, $(MI)_{\alpha=0} = 0.8$, $L_{f1} = L_{f2} = 0.75$ mH, $L_s = 6.12$ mH, $X_s = 2.45 \Omega$, $R_b = 0.5 \Omega$.

It is found that the maximum α is limited to 30 degrees under the above mentioned condition.

6. Experimental results

6.1 Equipment A prototype trial equipment of VSI installed its parts in a box (W255 mm $\times$ H248 mm $\times$ D410 mm).

Table 1 shows design parameters of a trial manufacture of VSI (Fig. 1.).

6.2 Experimental waveforms Fig. 6 gives the experimental waveforms of the voltage and the current when $\alpha = 25^\circ$, $MI = 0.93$, $E_d = 157$ V, $I_d = 8.4$ A, $E_u = 86$ V, $I_u = 14$ A, $p.f. = 1$.

The output current i_u is divided i'_{u1} through L_{f1} and i'_{u2} through L_{f2} . Each current varies sinusoidally with repetition of increase at the power supply mode and decrease at the circulating current mode according to the individual PWM pattern.

The ripple of the sinusoidal output current i_u which equals to the sum of two currents i'_{u1} and i'_{u2} is smaller than those of two current.

(a) $\tilde{i}_d$ of LC equipped circuit

(b) I_d of LC equipped circuit

(c) $\tilde{i}_d$ of EDLC equipped circuit

(d) I_d of EDLC equipped circuit

Fig. 7. Frequency spectra ($f_c = 4$ kHz)

As the ripple of current i'_u is filtered by C_f , the waveform of the output current i_u becomes perfectly ideal sine wave.

On the other hand, the ripple of dc current i_d will become a pulsating current at twice of the utility frequency.

Fig. 6(a) shows the ac component $\tilde{i}_d$ included i'_d is bypassed through the series resonance circuit $L_d C'_d$.

Fig. 6(b) shows the ripple of dc current i_d included i'_d is absorbed in C_d (EDLC).

Therefore, the current I_d from the battery storage becomes a flat dc current.

6.3 FFT analysis of experimental waveforms Fig. 7 shows the experimental frequency spectra of the $\tilde{i}_d$ and I_d use to FFT analyzer.

Fig. 7(a) and (b) shows the LC-equipped circuit. Fig. 7(c) and (d) shows the EDLC-equipped circuit.

LC-equipped circuit and EDLC-equipped circuit obtained a similar result.

7. Conclusions

In this paper, the VSI circuit configuration, the principle

of the composite PWM methods and measured by experiment are described. The experiments prove that the smooth dc current is obtained by using the EDLC. The experimental waveforms obtained a similar result with LC series resonance circuit. The EDLC-equipped circuit is able to lighter weight than a LC -equipped circuit. This paper also shows the composite PWM strategy with two types of the patterns contributes to reduce the ripple of the current.

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