Three-Phase PWM AC-to-DC Converter with a Wide Control Range of DC Voltage

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The paper presents a three-phase PWM AC-to-DC converter that employs an inductive energy transfer mechanism (DC reactor). This converter has a wide control range of DC voltage by means of its step-up and step-down characteristics. The source current can be sinusoidally shaped in phase with the source voltage by means of the proposed PWM control strategy. The power factor becomes unity in the controlled range of DC voltage. The input filter parameters are decided. Then, waveforms of voltages and currents, input, output and dynamic characteristics are discussed by the computer simulation and their validity is confirmed by experiments.

Key words: Converter, PWM, Sinusoidal source current, Step up/down voltage

1. Introduction

The diversity of AC-to-DC converter applications in power electronic systems, makes the development of a universal AC-to-DC converter indispensable. Traditionally, conversion of AC power (from utilities or generators) to DC power disadvantages, including:

(1) High input current harmonic components
(2) Source current is not in phase with the source voltage
(3) Maximum input power factor of approximately 0.5
(4) Invariable output DC voltage

To improve these defects many attempts have been done[10]. The AC-to-DC converter with a thyristor bridge has the advantage of simple configuration. However, it has the characteristics of lower input power factor and much generation of lower-order harmonics. Recent evolution of high-power devices with high-frequency switching capability, such as bipolar transistors, gate turn-off thyristors (GTOs) and etc., have made possible the use of pulse width modulation (PWM) to improve the quality of supply current waveforms and power factor in the AC-to-DC converters[11-13].

The conventional PWM voltage-source AC-to-DC converters, which have also been used as inverters, are based on the step-up operations from the supply voltages to the DC output voltage, so that the lower output voltage cannot be realized[14-16]. On the other hand, when the PWM current-source AC-to-DC converters[17-19] are applied to voltage-source converters by connecting the filter capacitor at the output terminals, they have step-down characteristics[20-23]. However, if both step-up and step-down output voltages, which have to be continuously regulated, are desired, they can satisfy the requirement.

The new single-phase AC-to-DC source current converter with a step up/down voltage and high input power factor proposed in[24-25] has the defect point that it is necessary to have the large DC reactor in order to reduce the ripple in the DC reactor current and improve the source current waveforms.

Then, a three-phase PWM AC-to-DC converter, which has the distinctive feature of step up/down voltage as well as the single-phase PWM AC-to-DC converter[26-27], was presented[28]. The output capacitor and the DC reactor can be reduced remarkably compared with that in the single-phase one[29]. The ripple of the DC reactor current becomes smaller and the PWM control strategy becomes simple with a highly improved source current waveforms.

In order to verify the advantage of the three-phase PWM AC-to-DC converter with step up/down voltage, a prototype experimental stand of 3 kVA is built and the validity of the proposed converter is highly confirmed.
2. THREE-PHASE PWM AC-TO-DC CONVERTER

2.1 Circuit Configuration

Fig. 1 shows the proposed three-phase PWM AC-to-DC converter. It comprises an input filter, a diode bridge with six switches, a reactor in the DC link, a series connection of a diode and a capacitor parallel to the DC reactor. The input filter absorbs the harmonics produced by the PWM operation of the converter in order to improve the source current waveform.

Since the same operation occurs repeatedly by a π/3 term, it is sufficient to consider the operation in this term for the analysis. There are four operating modes in one term. The equivalent circuits of each mode are shown in Fig. 2. The operating modes and switching timings are shown in Fig. 3. The operation in each mode is as follows:

(a) mode 1: The switches S_{w2} and S_{w3} are conducting and the converter input current flows from a-phase to b-phase through the DC reactor. The energy is stored in the DC reactor and the capacitor C is discharged into the load.

Fig. 1. Three-Phase PWM AC-to-DC converter.

Fig. 2. Operating modes.

Fig. 3. PWM control strategy.
(b) mode 2: The switches Sw6 and Sw8 are conducting and the converter input current flows from c-phase to b-phase through the DC reactor. The energy is stored in the DC reactor and the capacitor C is discharged into the load.

(c) mode 3: No switch is conducting, then the DC reactor is disconnected from the AC source. Thus, the DC reactor current flows through the diode Dd into the capacitor and the load.

(d) mode 4: When the power of the system is very low, the current flowing in the DC reactor is small. Thus, id can be discontinuous due to the ripple. During this mode, no switch is conducting and the capacitor C is discharged into the load.

2.2 PWM Strategy

To make the source current in phase with the source voltage, the on-times of the switches are decided as shown in Fig. 3(a). Fig. 4 shows the control system of the three-phase PWM AC-to-DC converter. The two signal STb and STc are derived from the sinusoidal waves Sa, Sb, and Sc which are in phase with the source voltages ea, eb, and ec respectively.

The DC reactor current is detected through the current transformer (CT) and the output DC voltage is detected through the DC voltage transformer (DCVT). The difference between the DC voltage command v*c and the instantaneous value of the DC voltage is used as the input of the PI controller. Then, the generated two signals STh* and Stc* are multiplied by the output of the PI controller and divided by the DC reactor current respectively to produce the signals STh* and Stc* which are used references. After that, STh* and Stc* are compared respectively with fixed amplitude sawtooth-waveform to produce Ta, Tb, and Tc pulses as shown in Fig. 3(a). The frequency of the sawtooth-waveform is a switching one and is selected over 16 kHz to avoid the audio frequency. Fig. 3(b) shows that the on-times of the switches Sw1 to Sw4 are determined with the combination of Ta, Tb, and Tc by the use of a distributor based on analog switches.

2.3 Output Voltage Control

The DC voltage is controlled by regulating STh* and Stc* as follows:

\[ S_{Th}^* = \frac{S_{Th}}{I_d} \]
\[ S_{Tc}^* = \frac{S_{Tc}}{I_d} \]
\[ P_c = K_r e + K_i \int e \, dt \]
\[ e = v_c^* - v_c \]

where,

- \( K_r, K_i \) gains of the proportional control and the integral control
- \( v_c^* \) DC voltage command
- \( v_c \) DC voltage (output voltage)

3. Simulation Method

Denoting the voltage and current shown in Fig. 1, the state equation for each mode j is expressed as

\[ \frac{dX_j(t)}{dt} = A_j X_j(t) \]

where the state vector is defined by

\[ X_j(t) = [v_{a1}, v_{a2}, v_{b1}, v_{b2}, i_a, i_b, v_{fa}, v_{fb}, v_{fc}, i_d, v_c]^T \]

The matrix \( A_j \) of the system in each mode j is denoted by

**Fig. 4. Control system.**
PWM Converter

where

- number of sampling period \((t = mT)\)
- state transition matrix
- state vector in previous configuration.

The simulation is executed by the iterative computation of eq. (8), and the solution for each \(X\) component is obtained in the form of a truncated power series in \(t(mT)\). The computational method using \(A^m(=e^{At})\) results obviously in the asymptotic solution of \(X\) for small \(t\).

### 4. Characteristic Formulations

The transfer function of the equivalent circuit of the AC-to-DC converter, shown in Fig. 5, is obtained by

\[
G(\omega) = \frac{1}{1 - (\omega/\omega_0)^2 + j\omega R/C_f} \quad (9)
\]

where

\[
\omega_0 = \frac{1}{\sqrt{C_f L_f}}
\]

To predict the source current:

**First**: as shown in Fig. 5 (b), both side of the current \(i_{ra}\) are supposed open, and the source voltage \(e_a = E_s \cos \omega t\). Then, the current loop \(i_{ra}'\) is expressed by

\[
i_{ra}' = -\omega C_s E_s |G(\omega)| \sin \omega t \quad (10)
\]

**Second**: as shown in Fig. 5 (c), both side of the source \(e_a\) are supposed short, and the switching function \(SF = \sum k A_k \cos k \omega t\) \((k\) is the harmonics order). Then, the currents \(i_{ra}, i_{ra}'\), and \(i_{ra}''\) are expressed by

\[
i_{ra} = L_s SF = \sum I_k \cos k \omega t
\]

\[
i_{ra}' = i - i'
\]

\[
i_{ra}'' = i_{ra} - i_{ra}''
\]

where

\[
I_k = L_s A_k, \quad I_{ra} = I_{ra} |G(\omega)|
\]

Then, the total currents \(i_s\) and \(i_{ra}\) flowing into the capacitor and the inductor of the filter, respectively, can be denoted by

\[
i_s = i_s + i_{ra}'\quad \text{and}\quad i_{ra} = i_{ra}'' - i_{ra}'\quad (12)
\]

the fundamental component of the source current \(I_{ra,1}\) is equal to \(I_{ra,k}\) when \(k = 1\).

As shown in Fig. 7 the fundamental component of the

\[
X_1(m) = \Phi_1(m) X_1(m_0) \quad (8)
\]

where

- number of sampling period \((t = mT)\)
- state transition matrix
- state vector in previous configuration.

![Fig. 5. Equivalent circuit of single phase filter.](image)

![Fig. 6. Bode diagram.](image)
source current $I_{a1}$, which is the sum of the fundamental components of the $I_{m1}$ and $I_{m2}$, is lagging of $\phi_1$ to the source voltage. Then $\phi_1$ can be denoted by

$$\phi_1 = \tan^{-1}\left(\frac{I_{m2}/I_{m1}}{I_{m1}}\right) \tag{13}$$

### 4.1 Input and Output Characteristics Formulations

The distortion factor DF is expressed by

$$DF = \frac{\sqrt{\sum I_{a,n}^2}}{I_{a1}} \tag{14}$$

where

- $I_{a,n}$: $n$-th harmonics component of the AC source current
- $I_{a1}$: fundamental component of the AC source current

Then, the input power factor PF is expressed by

$$PF = \frac{1}{\sqrt{1+DF^2}} \cos(\phi_1) \tag{15}$$

where

- $\cos(\phi_1)$: the displacement power factor

The ripple factor is expressed by

$$\varepsilon_p = \frac{V_{c_{max}} - V_{c_{min}}}{\bar{V}_c} \times 100 \tag{16}$$

where

- $V_{c_{max}}$, $V_{c_{min}}$: maximum value and minimum value of DC voltage
- $\bar{V}_c$: average value of the DC voltage

### 4.2 Reactive Volt-ampere Formulations

The volt-ampere (VA) ratings of the reactive components of the system are defined in the following. The volt-ampere rating of an inductor is

$$LVA = \sum\left(\frac{I_{i,n}}{\sqrt{2}}\right)^2 \times nX_i \tag{17}$$

The volt-ampere rating of a capacitor is

$$CVA = \sum\left(\frac{I_{c,n}}{\sqrt{2}}\right)^2 \times \left(\frac{X_c}{n}\right) \tag{18}$$

where

- $I_{i,n}$: $n$-th harmonic component of current flowing in the electrical component
- $X_i$: reactance of an inductor
- $X_c$: reactance of a capacitor
- $k$: greatest harmonic order supposed to appear in the system

The input filter VA rating (FVA) is

$$FVA = 3(L_VA + C_VA) \tag{19}$$

where

- $L_V$: rating of the input filter inductor
- $C_V$: rating of the input filter capacitor

and the total VA ratings (TVA) of the reactive components of the system is

$$TVA = FVA + LVA + CVA \tag{20}$$

where

- $LVA$: rating of the DC inductor
- $CVA$: rating of the DC capacitor

### 4.3 Percent-Impedance Formulations

The percent-impedance of the filter inductor and the DC reactor are denoted by

$$L(\%) = \frac{3L_{\omega L}}{P_n} \tag{21}$$

$$L(\%) = \frac{L_{\omega L}}{P_n} \tag{22}$$

where

- $P_n$: nominal power of the system
- $I_a$ and $I_d$: nominal rms values of the source and DC reactor currents (for $P_n=3$ kVA, $I_a=8.66$ A and $I_d=22$ A).

### 5. Decision of Filter Parameters

As shown in Fig. 5, the input filter is an L-C type used to attenuate the lowest harmonic produced by the PWM operation of the converter in order to improve the waveform of the source current. Then, the higher harmonics are adequately reduced to a permissible level. This results because the resonance frequency of the input filter is decided to be below the lowest harmonics produced by the switching frequency and far above the source frequency\(^{17}\). Thus, the harmonics present occur in the frequency range where the input filter attenuation curve has the characteristics of 40 dB/decade as shown in Fig. 6.

It is relatively simple to determine the required L-C product to attenuate harmonics at given amount. However, the values $L_V$ and $C_V$ are still undetermined.

For the design of the converter input filter, several design specifications are of interest. In this investigation, the limitation of the minimum displacement power factor, the maximum distortion factor and the TVA of the reactive components of the system are considered as a design specifications.

Fig. 8 shows the decision method of the input filter parameters. The DC voltage command is 300 V and the load resistance is 45.3 $\Omega$, the resonance frequency of the input filter is 1592 Hz and the switching frequency is 16200 Hz. The increase of the filter capacitor value defects the displacement power facto ($\cos(\phi_1)$). Then,
to gain good displacement power factor, the maximum displacement angle between the source current and the source voltage is limited to 2.6 degrees. On the other hand, the cost (TVA) increases rapidly with the small value of $C_f$. Then, to minimize the cost, the maximum TVA is limited to 1.0 p.u. (3 kVA). The capacitor value can be selected from the intersection region. For this system, $C_f = 10 \mu$F is chosen as optimal value of the system, which corresponds to 1.0 mH of the filter inductance.

6. Steady State Characteristics

The experimental system of the three-phase PWM controlled AC-to-DC converter is shown in Fig. 4. It is composed of the main power circuit, the driving circuit and the control circuit. The IGBT is used as a switching device. The circuit constants and condition are listed in Table 1.

6.1 Waveforms

Fig. 9 shows the simulation and experimental voltages and currents waveforms of the three-phase PWM AC-to-DC converter. The DC voltage command is 300 V and the load resistance is 45.3 $\Omega$.

The simulated waveforms agree well with the experimental ones. The source current is a quasi-sinusoidal waveform and in phase with the source voltage. The DC reactor current pulsates in 1/6 cycle of the source voltage. The waveform of the output capacitor voltage is a DC one.

Fig. 10 shows the spectrums of the source current, the converter current, and the DC reactor current respectively. The experimental conditions are the same as in Fig. 9.

In Fig. 10 (a), the low order harmonics are almost eliminated and the harmonics produced by the switching frequency are reduced to 1.8% of the fundamental component. In Fig. 10 (b), the low order harmonics are not higher compared with that produced by the switch-
ing frequency. Then, the filter capacitor alone can minimize them. The size of the filter parameters can be minimized by choosing the resonance frequency far above the source frequency.

Fig. 10 (c) shows that the harmonics produced by the resonance frequency in the DC reactor current can be reduced to a minimum level only by the use of the DC reactor instead of other devices.

6.2 Input and Output Characteristics

Fig. 11 (a) shows the input and output characteristics of the converter versus the DC voltage command. The load resistance is 45.3 $\Omega$.

This converter can control the output voltage from almost zero to more than the maximum value of the source voltage. The distortion factor becomes larger when the DC voltage becomes smaller. That is because the ratio of the components due to the anti-resonant of the input filter to the source current gets larger in the small range of the DC voltage command. The input power factor is unity above the DC voltage command of about 150 V. However, it becomes rapidly lower under this DC voltage command. That is because the displacement power factor becomes smaller rapidly due to the leading input filter current. The ripple factor increases with the increase of the DC voltage command. However, it is considerably small.

Fig. 11 (b) shows the input and output characteristics of the converter versus the resistance of the load. The DC voltage command is 300 V. The experimental results are conform to that of the simulation one and all are in an acceptable range to be valid for the practical use. The operating mode 4 does not appear in the
PWM Converter

control range of Fig. 11 (a) and (b).

Fig. 12 (a) shows that the DC voltage is almost regulated from about 50 V to more than the maximum value of the source voltage by changing the DC voltage command. However, under 50 V, the DC voltage is larger than the DC voltage command because of the same reason as in Fig. 11 (a).

Fig. 12 (b) shows that the DC voltage can be regulated at the DC voltage regardless of the change of the load resistance. However, in a large load resistor or a small DC voltage command, the mode 4 appears and makes the PWM control strategy unsuccessful.

7. Dynamic Characteristics

A large value of DC reactor and output capacitor are undesirable. On the other hand, a small value of DC reactor and output capacitor are also undesirable for the following reasons:

1. A small value of DC reactor makes the control difficult due to the discontinuous mode of $i_d$.

2. A small value of output capacitor is dangerous for the system. Because it increases the variations of the DC voltage during the load change and makes the control difficult.

For $K_r=0.04$ and $K_i=0.02$, $C=820 \mu$F and $L=3$ mH are chosen by simulation as optimal values of the system.

Fig. 13 shows the simulation and the experimental results of the response for the step-up/down change of DC voltage command from 200 V to 300 V where the value of the load resistance is equal to 45.3 $\Omega$. Fig. 14 shows the simulation and the experimental results of the response for the step-up/down change of the load resistance from 69.3 $\Omega$ to 45.3 $\Omega$ where the value of the DC voltage command is equal to 300 V. The circuit constants and conditions are listed in Table 1.

In Fig. 13, the simulated response of DC voltage has a settling time about 0.05 second. However, the experi-
mental one has a settling time more larger. That is due to the effect of the heat losses in the system on the parameter change of the circuit components. In this period, the DC reactor current and the source current become large due to the energy storage in the DC reactor. After that, the DC voltage and the source and the DC reactor currents become in steady state.

To test the performance of the system during the load change, simulation and experiment were carried out as shown in Fig. 14. The simulated response of DC voltage has a settling time about 0.025 second. However, the experimental one has a settling time more longer. That is because the loss acts as parameter changer in practice. The variation of the DC voltage is suitable for the practical use. After this period, the DC voltage and currents of the source and the DC reactor become in steady state.

8. Conclusions

In this paper, the three-phase PWM AC-to-DC converter with a small DC reactor is proposed. A PWM control strategy and the decision of the input filter parameters are presented. The control characteristics are discussed by the computer simulation and confirmed by experiment. It is found that the source current is a sine wave in phase with source voltage and the power factor is unity in the wide range of the controllable DC voltage. The distortion factor and the ripple factor are very small. Therefore, the DC reactor value is considerably reduced compared with that in literature(12)(13). It has a fast dynamic response. Moreover, the transient source currents cannot disturb the power system. Consequently, we believe that the AC-to-DC converter presented in this papers is suitable for the practical use which need a good quality AC current and a widely controlled output voltage.

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References

(13) S. Funabiki, N. Toita & A. Mechi: "A single-phase PWM AC to DC converter with a step up/down output voltage and sinusoidal supply current", IEEEIAS 1991 Annual Meeting Record, p. 1017
(14) A. Mechi & S. Funabiki: "A step up/down output voltage PWM AC to DC converter with one switching device", IEEE Pecedings-B, 140, No. 1, 35 (1993-1)
(15) A. Mechi & S. Funabiki: Three-Phase PWM AC to DC converter with a step up/down voltage, IEEE IAS 1992 Annual Meeting Record, p. 703
(16) A. Mechi & S. Funabiki: Effect of the Output Parameters on the Dynamic Performances of the Three-Phase PWM AC to DC Converter”, Joint Conf. of Elec. and Inf. in Chugoku Branch, p. 12 (1993)

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