Various Harmonic Characteristics of SVC using NPC-PWM Inverter

Ryuji Ishida*, Keiju Matsui*
*Chubu University
Kasugai 4878501, Japan
Phone:+81-568-51-1111, Fax:+81-568-51-1141
E-Mail: keiju@isc.chubu.ac.jp

ABSTRACT

An NPC-inverter has significant advantages over other types of inverter, such as the ability to drive a motor with a nearly sinusoidal current waveform, and at higher output voltages. Consequently, the consideration of practical applications for this type of inverter is of increasing interest. These applications include larger capacity inverters, where using an NPC-inverter is particularly beneficial. These are being put into practical use in areas such as large ac motor drives, SVC’s (Static Var Compensators) and the like. In this paper we will discuss the harmonic characteristics in applications where the NPC-inverter is used with an SVC.

1. INTRODUCTION

NPC-inverters have significant advantages over other types of inverter, such as the ability to drive a motor with a nearly sinusoidal current waveform, and at higher output voltages. Consequently, the consideration of practical applications is of increasing interest. These applications include larger capacity inverters, where using an NPC-inverter is particularly beneficial. These are being put into practical use in areas such as large ac motor drives, SVC’s (Static Var Compensators) and the like. In this paper we will discuss the harmonic characteristics in applications where the NPC-inverter is used with an SVC.

Extremely large capacity SVC’s need to be equipped with some form of frequency filter. Under such conditions, certain specified harmonics should be kept at an almost constant frequency. Studies have shown that a symmetrical modulation strategy could be applied to an SVC more effectively than an asymmetrical one.

2. CIRCUIT CONFIGURATION AND OPERATION

Fig.1 shows the main circuit configuration of an NPC-PWM inverter with respect to phase u, which is one of the three phases present. Fig.2 (a) shows details for symmetrical modulation and Fig.2 (b) shows details for asymmetrical modulation. The circuit plays the role of an SVC by means of comparing the phase difference between the modulation sinusoidal signal and the supply voltage waveform, in which the output current can be controlled by adjusting the phase difference. In this paper, we will make a comparison between the two modulation strategies and discuss them from the point of view of their harmonic characteristics.

The signals for the main switches are generated by one of the following processes. In the example shown in Fig.2 (a), the two carriers $e_c$ and $e_c'$ are shifted in phase by 180 deg. with respect to each other. Consequently, the carrier waveform that we obtain becomes symmetrical...
relative to the zero axis, so we call this a symmetrical modulation. In the example shown in Fig. 2 (b), the two carriers \( e_r \) and \( e_r' \) are of different polarity and shifted in phase by 180°, as shown. In this case, the carrier waveform obtained becomes asymmetrical relative to the zero axis, so we call this an asymmetrical modulation. The triangular wave and the sinusoidal wave are compared for both types of modulation.

\[
\begin{align*}
\text{when } & e_u > e_r \text{ and } e_r', \text{ then } v_u = V_1, \\
\text{when } & e_r > e_u > e_r', \text{ then } v_u = 0 \quad \ldots(1) \\
\text{or } & e_r' > e_u > e_r, \text{ then } v_u = -V_1.
\end{align*}
\]

This equation is applicable to both modulation strategies. The SVC is used to adjust the reactive power in the power system, so in general, from the point of view of the intended application, the capacity of the equipment becomes much larger. Consequently, the output voltage waveform obtained should satisfy the following conditions, i) three phase symmetry, ii) odd or even function symmetry and iii) half wave symmetry. The phase of the carrier triangular wave in Fig. 2 should be made to shift along with the shift of the sinusoidal wave, in accordance with the inverter control, so that the waveform can be kept symmetrical at all times.

Fig. 3 explains the reason for the particular symmetry of the asymmetrical modulation. The phase of the carrier in the figure is represented in a similar representation as the symmetrical modulation in order to compare it to the case where we have symmetrical modulation, i.e. the distance to the next carrier is shown to be \( \pi \) radians. Period A of \( e_m \) (which consists of one period of the symmetrical wave), is represented by \( n \pi \) in the center and by \( \pi/4 + \pi/4 = \pi/2 \) at both ends, where \( n = 1, 2, 3, \ldots \) is the number of the carrier triangular wave during period A. In the figure, only one carrier triangular wave is shown, i.e. \( n \) becomes unity. In order to make the waveform symmetrical with regard to the three phases, the relationship of the carrier phase is given by \( 3 \times (n \pi + \pi/2) \). Rearranging these results, the frequency ratio for the symmetrical modulation is

\[
f_r / f_s = 3n \quad (n=1,2,3\ldots)
\]

and for the asymmetrical modulation is

\[
f_r / f_s = 3(n+1/2) \quad (n=1,2,3\ldots)
\]

In the example in Fig. 3, where \( n = 1 \), then the frequency ratio becomes \( f_r / f_s = 4.5 \). It is very interesting to note that the frequency ratio is not an integer, yet it produces a symmetrical three-phase waveform.
3. SIMULATION RESULTS AND DISCUSSION

The circuit constants used throughout this chapter are as follows. The modulation factor \( a = 0.9 \) and the dc capacitance = 3000 \( \mu \text{F} \). The supply frequency \( f_s \) is 60Hz, the triangular carrier frequencies are 540Hz for the symmetrical modulation and 630Hz for the asymmetrical modulation. Fig.4 shows the characteristics of the capacitor voltage \( V_1 (=V_2) \) and the load current \( i_L \) for varying phase difference \( \theta \) of the modulating sinusoidal signal relative to the supply voltage waveform. In the case where \( \theta < 0 \), \( e_s \) lags, so the output current leads. In the case where \( \theta > 0 \), \( e_s \) leads, so the output current lags. The vector diagrams of these operations are shown in Fig.5. As can be seen on the left in Fig.4, \( V_1 \) is increased when \( i_s \) leads in the region where \( \theta < 0 \), compared to the region shown on the right side where \( \theta > 0 \) and \( i_s \) is lagging. The reason for this can be explained from the vector diagrams in Fig.4.

Fig.6 shows harmonic analyses of the output current by circuit simulation. The fundamental current necessary for the SVC can be effectively controlled. On the other hand, the harmonic components remain almost constant over the whole region, except for the 17th and 19th harmonics, which are caused by the carrier switching frequency. For the asymmetrical modulation, almost all of the harmonic components are fairly suppressed, but the degree of suppression of the harmonics is insufficient as compared to the case of symmetrical modulation, except for the 17th and 19th harmonics. If these harmonic components could be easily eliminated by a resonant filter or the like, these characteristics are not degrade than for asymmetrical modulation. In the region where \( \theta < 0 \), the harmonic components, (especially the 17th and 19th), are increased a little compared to the region where \( \theta > 0 \), since the capacitor voltage is increased in this region and harmonics are also increased.
Fig. 7 shows the relationship between the modulation factor and the harmonic components of the output current. For the symmetrical modulation in Fig. 7 (a), the fundamental components remain constant, (except below about $a = 0.5$), but the 17th and 19th harmonics gradually increase as the modulation factor is reduced. The reason for this is that the pulse width of the output voltage narrows and the capacitor voltage is increased, so that the harmonics gradually grow. As the modulation factor is still further reduced to below about $a = 0.4$, the fundamental component is gradually reduced. The reason for this can be explained as follows. In those regions where the modulation factor is reduced, the increase of the capacitor voltage is suppressed due to circuit losses, voltage drop on the inductor and the like, and then the fundamental current is also reduced. When the modulation factor is reduced still further, the power supply circuit is scarcely connected across the dc capacitor, but for a short period is connected to a neutral point. The circuit consists of a power supply and inductor $L$ dominantly, and yet the output current changes from leading to lagging, so it cannot yet perform the function of an SVC. Taking this into consideration, the lower limit of the modulation factor for the SVC would be about $a = 0.5$ or 0.6.

On the other hand, the characteristics of the asymmetrical modulation could be explained in a similar manner. As you can see, for the symmetrical modulation, except for of the 17th and 19th harmonics, the rest of the harmonics are almost suppressed for the normal modulation region from $a = 0.5$ to about $a = 1.0$. However, compared to this, even though the harmonics are effectively suppressed for the asymmetrical modulation in Fig. 7 (b), various other harmonics remain over a wide range, as shown. Below $a = 0.5$, due to an increase in the harmonics and the like, the fundamental component is reduced to $a = 0.3$, and then dramatically increased in the same way as that just mentioned. On the other hand, for the over-modulation region of both modulation strategies, various other harmonics are generated, but the fundamental component is kept almost constant.

Fig. 8 shows the characteristic of the capacitor voltage, $V_c$ ($=V_S$) in Fig. 1. As the modulation factor is gradually reduced toward $a = 0$, the capacitor voltage is increased according to the principle of a boost chopper. In the region where the modulation factor reduces still further, the function of the SVC is lost. Since the current is greatly increased, the capacitor voltage is reduced, due to the impedance voltage drop.

Fig. 9 shows the distortion factors for both modulation strategies. The definition of the distortion factor is shown in the figure. In order to take into account the order of the various harmonics, the distortion factor is given a weight related to the order, as shown. Except for the lower modulation region below $a = 0.8$. However, in the higher modulation region, especially at the vicinity of $a = 1.0$, the symmetrical modulation with $f_r = 540$Hz has the comparable distortion factor as compared to the
asymmetrical modulation having the higher carrier frequency of $f_c = 630\text{Hz}$. From such results, we can say that the symmetrical modulation strategy could be better than the asymmetrical one in the region suited to practical applications. In general, it is believed that asymmetrical modulation is superior to symmetrical modulation for inverter drives, just like it is for motor drives. In the SVC, however, this theory does not apply. We can explain the reason for this by referring to Fig.10. This figure shows the weighted distortion factor of the input current in an inverter drive with dc power supplies instead of the capacitors used for the SVC. As shown in Fig.10 (b), at high power factors (above about $\text{pf} = 0.97$), the asymmetrical modulation is better than the symmetrical one. At power factors below that value however, the symmetrical modulation is superior to the asymmetrical one. One of the reasons for this is explained in Fig.11, as follows. In asymmetrical modulation, the phase of the carrier triangular wave is different between the positive wave and the negative wave, so each harmonic can effectively be cancelled between the different phases. The condition of cancellation between the $u$ phase and the $v$ phase is represented in Fig.11. During period I, the output current waveform is generated effectively under conditions where there is harmonic cancellation. On the other hand, during period II, the current waveform is generated ineffectively because during this period each phase of the carrier signal is identical, and so there is no harmonic cancellation. As shown in Fig.11 (b), where $\text{pf} = 1$ for a typical inverter load, the current $i_u$ is in phase with $v_u$, and the current shown in the hatched area is generated under conditions represented by the harmonic cancellation theory. In the same way, Fig.11 (a) shows the condition for $\text{pf} = 0$, where, like the SVC, the current leads by $90^\circ$, and then the hatched current is generated in a similar way under harmonic cancellation with two different phases of carrier. If we make a comparison between the two hatched areas, we can see that the area
where \( pf = 0 \) is reduced to 75.8% of the value where \( pf = 1 \). As a result, we can say that the asymmetrical modulation strategy is more suitable for a conventional inverter drive, and is less effective for an SVC, where it’s effectiveness is slightly reduced. The characteristics previously mentioned in Fig.10 illustrate the results of these discussions.

4. CONCLUSIONS

In this paper, various harmonic characteristics that are applicable to SVC’s are discussed, and a comparison is made between two different modulation strategies. In an extremely large capacity SVC, which should be equipped with various frequency filters, it is desirable that certain specified harmonics remain almost constant in frequency, and that the rest of harmonics can be effectively suppressed. The symmetrical modulation strategy is useful from this point of view, so it could be applied to the SVC. It would seem that the asymmetrical modulation strategy is better than the symmetrical approach at higher power factors. However, at lower power factors, such as those used for an SVC, the symmetrical modulation strategy is superior to the asymmetrical one.

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