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A New Space Vector Modulation Strategy for Common Mode Voltage Reduction

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***Abstract* - In this paper the impact of the inverter modulation strategy on common mode conducted emissions is addressed. Whereas typically passive filter designs are used to mitigate the common mode current produced by the inverter, active filtering is proven to greatly reduce common mode conducted emissions due to the modulation of the converter. A new space vector modulation strategy is presented for common mode EMI reduction in three and four phase converters.**

I. INTRODUCTION

An extensive number of pulse width modulation strategies for three phase inverters have been investigated in the last 20 years. One criterion of comparison between these modulation techniques is the weighted total harmonic distortion on the inverter output line to line voltage (WTHD) [1]. In general the performance of the different modulation strategies is evaluated by looking at the resultant output differential voltages and their spectrum. Only recently some attention has been given to the common mode voltage generated by the inverter [2] and to the impact that the inverter modulation techniques have on common mode conducted emissions [3]. Typically, passive filter designs are used to mitigate the common mode current produced by the modulation strategy chosen.

Recently a new active topology, obtained by adding a fourth phase to a typical three phase inverter has been proposed by the authors [2]. In this paper the impact of the converter modulation strategy is discussed for the four phase topology and for typical three phase inverters. In addition two new space vector modulation strategies are proposed as ideal to control the four pole inverter and useful for common mode emission reduction in typical three phase inverters.

II. COMMON MODE VOLTAGE IN TYPICAL THREE PHASE INVERTERS

The common mode voltage which is produced by three phase inverters is very closely related to the instantaneous average output voltage. By looking at the three phase inverter shown in Fig. 1 the common mode voltage can be expressed:

$$V_{avg\_outl}(t) = \frac{V_1(t) + V_2(t) + V_3(t)}{3} \tag{1}$$

Equation (1) is in fact the neutral voltage to ground for balanced 3 phase loads with an infinite common mode impedance.

In real systems a parasitic capacitive coupling exists between the load and ground. For instance when the load is a motor, capacitive coupling exists between the motor windings and the motor frame, which is grounded. This parasitic capacitance creates a path for the common mode current to flow from the load through earth ground and back to the source. Capacitive coupling of a three phase RL load is depicted in Fig.1 where a typical common mode current path is also shown.

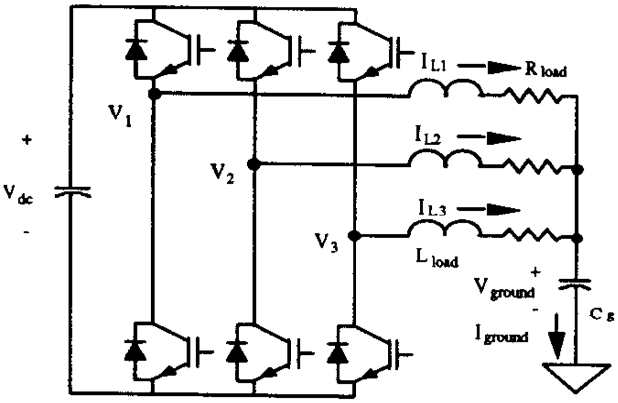


Fig.1 Schematic of a typical three phase system with common mode current path

Common mode currents cause conducted EMI, damage to motor bearings, activation of ground fault detection circuits and heating of conduit where it flows.

The common mode choke, which is a big part of passive filters, is inserted between the inverter and the load to increase the common mode impedance, attenuating the common mode current. However a common mode choke can become large, heavy and expensive.

The spectrum of a typical common mode voltage is large at the frequencies around the switching frequency of the inverter. The common mode energy located at these frequencies is produced by the average output voltage expressed in Eq. (1). Such a voltage is controlled by the modulation strategy of the inverter.

Therefore, the common mode current can be actively reduced by properly controlling the inverter. It can also be reduced to zero by using a converter topology that achieves symmetry, as is discussed in the following section.

III. THE FOUR PHASE CONVERTER

In order to reduce to zero the average output voltage, it is necessary that the inverter has an even number of legs. By adding a fourth phase to a typical three phase inverter this goal is achieved and the common mode voltage can be greatly reduced if the following modulation constraint is satisfied:

$$V_1 + V_2 + V_3 + V_4 = 0 \tag{2}$$

It is important to note that Eq. (2) implies that two top switches and two bottom switches have to be on at all times. This also means that no zero state (the three top or bottom switches on at the same time) is allowed when controlling a four phase inverter.

The four leg inverter topology, recently presented by the authors [2], is shown in Fig. 2. The second order filter inserted between the inverter and the load guarantees sinusoidal output currents.

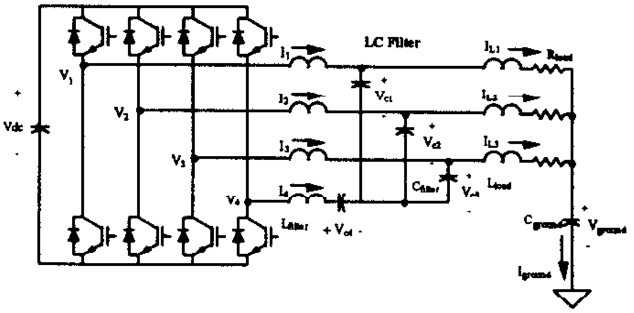


Fig. 2 Schematic of a four phase inverter with a three phase load and common mode path

Any modulation strategy can be modified to satisfy the constraint expressed by Eq. (2), and therefore used to control a four pole inverter. It can either be a soft or hard switching voltage source inverter (VSI). Experimental measurements on a four pole soft switching converter have been presented earlier [2] in order to prove that the common mode voltage is reduced significantly with respect to a traditional three phase topology.

Although the soft switching four pole converter has given good results, there is presently more interest on hard switching inverters, since they are to date the majority of the solid state converters. As a first stage the concept was proven on a PWM inverter by adding the required hardware and modifying the modulation strategy to satisfy the constraint in Eq. (2). To achieve this goal PWM sine-triangle with three carriers was used to control the four pole inverter. It can be shown that by comparing the three sinusoidal reference voltages with three triangle waveforms shifted by 120 degrees, the zero is not chosen when the modulation index is not greater than 0.66. The fourth phase is therefore switched according to the constraint expressed in Eq. (2).

With this modulation strategy the common mode voltage produced by a four leg VSI is noticeably smaller then that existing in a typical three phase inverter, as is shown in Fig. 3. In this picture the common mode voltage produced by a three phase inverter is compared with that produced by the same inverter when the fourth phase is enabled. It should be emphasized that the two topologies are compared on the same hardware. The switching frequency of the converter is limited to 3 kHz due to limitation imposed by the DSP used to control the converter.

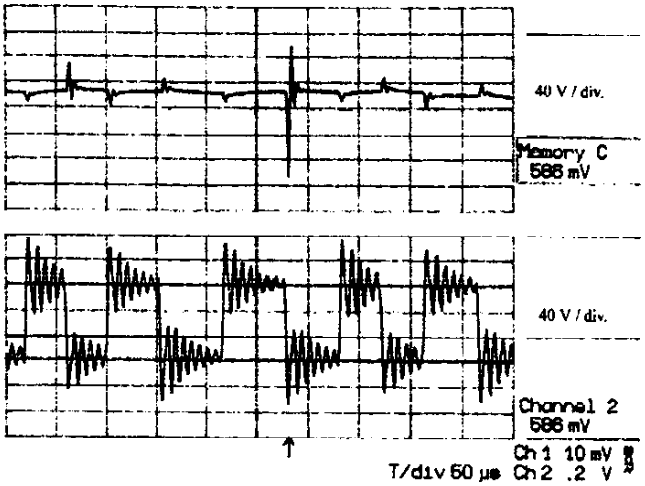


Fig. 3 PWM sine-triangle: Machine neutral voltage with respect to ground with (upper) /without (lower) fourth phase operation

In Fig. 4 the spectra of the common mode voltages for both topologies are reported to demonstrate, once again, that the four phase topology can significantly reduce the common mode voltage produced by a typical three phase inverter.

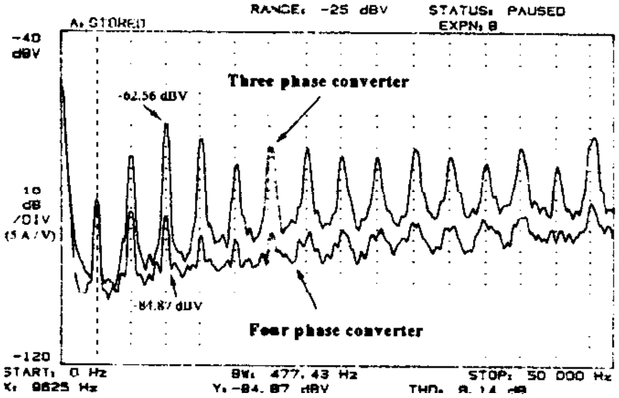


Fig. 4 PWM sine-triangle: Spectra of the machine neutral voltage with respect to ground

Although the experimental results shown above prove the validity of the four phase topology for a hard switching inverter, at the same time the modulation strategy used to control the inverter is limited to a modulation index not larger then 0.66. This is frequently an unsatisfactory penalty to pay in order to reduce the common mode voltage.

In order to overcome the limitation on the maximum output voltage with PWM sine-triangle modulation, space vector theory has been examined as a means for common mode voltage reduction.

IV. NEW SPACE VECTOR MODULATION STRATEGIES

It is useful to consider a typical space vector pattern by referring to Fig. 5.

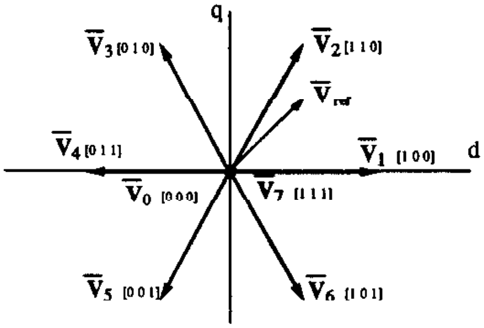


Fig. 5 Space vectors on the d q plane

One can define the modulation index as the ratio between the amplitude of the reference voltage vector and the amplitude of the space vectors:

$$M_i = |V_{ref}|/|V_1| \tag{3}$$

In typical space vector modulation strategies the maximum modulation index obtained is 0.86.

The reference vector, V_{ref}, placed on the d-q plane, is constructed by averaging the two nearby active space vectors and the zero state vectors. In other words the switching pattern is obtained by selecting the nearest two active space vectors of the six available and filling the rest of the switching period with zero space vectors V_0 and V_7 [1]. In the particular example of Fig. 5, where the reference vector is located between 0 and 60 degrees, the two active vectors are V_1 and V_2 and the time spent on each of the active space vectors is determined by equations (4) and (5):

$$\overline{V}_1 T_1 + \overline{V}_2 T_2 = \overline{V}_{ref} \frac{T_s}{2} \tag{4}$$

$$\frac{T_s}{2} = T_1 + T_2 + T_3 \tag{5}$$

where T_s is the switching period, T_1 and T_2 are the times spent respectively on the two active space vectors V_1 and V_2 adjacent to the reference vector. T_0 is the time spent on the zero space vectors V_0 and V_7. Equation (4) is a vector equation, which yields two scalar equations when projected on the q and d axes:

$$V_{1q} T_1 + V_{2q} T_2 = V_{qref} \frac{T_s}{2} \tag{6}$$

$$V_{1d} T_1 + V_{2d} T_2 = V_{dref} \frac{T_s}{2} \tag{7}$$

where V_{qref} and V_{dref} are the projections of the reference vector on axes q and d respectively.

By solving equations (5),(6) and (7) the three times T_1 T_2 and T_3 are computed. Therefore the reference voltage can be constructed by the switching pattern shown in Fig. 6.

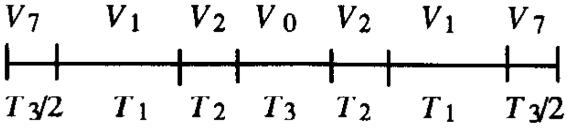


Fig. 6 Switching pattern for typical space vector modulation

The common mode voltage produced by this space vector modulation is not zero. The effect of this modulation technique on the common mode voltage produced by voltage source inverters (VSIs) and its amelioration is the focus of the proposed modulation strategies.

A. First space vector modulation

The first step towards the control of a four pole inverter is to eliminate the zero states by replacing them with two other active states, adjacent to the original two active states used in the traditional modulation technique. In the example of Fig. 5 vectors V_6 and V_3 are selected.

The first modulation strategy is obtained by using the same times T_1 T_2 and T_3 computed for a typical space vector modulation strategy, but with the switching pattern shown in Fig. 7.

In Figs. 8 and 9 the simulated time domain waveforms of the common mode current, I_{ground}, are plotted respectively for a three phase inverter controlled by a traditional space vector modulator and a four phase inverter controlled with the new modulation strategy. Note that for an effective comparison between the four phase and the three phase topology, a second order filter is inserted between the inverter and the load in the three phase topology. The values of all the filter and load components are the same in both models. The modulation index is 0.8 for both simulations.

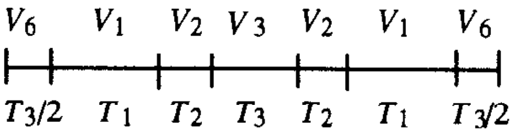


Fig. 7 Switching pattern for the first space vector modulation without the zero state

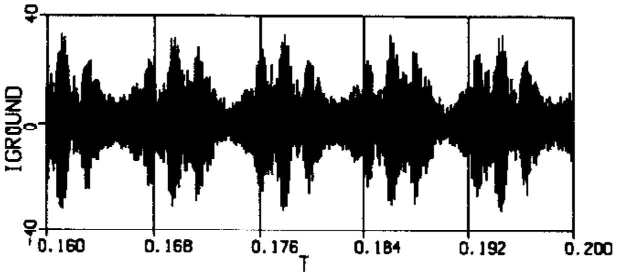


Fig. 8 Ground current in a three phase inverter controlled with traditional space vector modulation

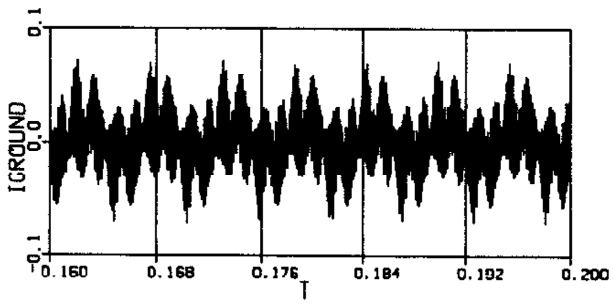


Fig. 9 Ground current in a four phase inverter controlled with the new space vector modulation

Figs. 8 and 9 show that when the new modulatio strategy is used to control a four phase converter th common mode current is more the 100 times than a thre phase inverter controlled with the traditional space vecto modulator.

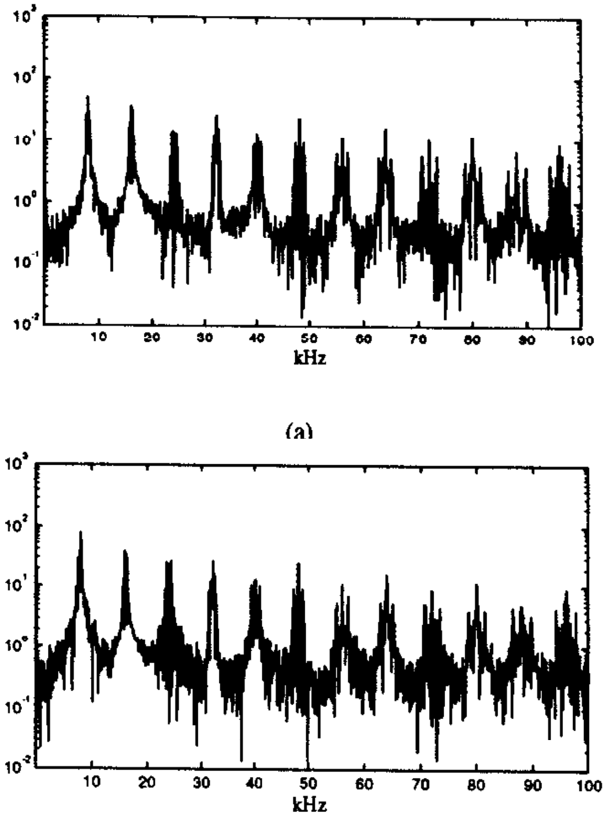
The advantage of this new space vector modulation strategy with respect to PWM sine-triangle with three carriers, is that there is no limit on the output voltage that can be produced by the VSI.

The penalty for common mode current reduction is a small distortion in the line to line output voltage when the new modulation strategy is used. In Fig. 10 the spectra of the line to line voltage at the output of the inverter (before the filter) for the old and new space vector modulation are compared up to 100 kHz. In Fig. 11 the spectrum of the difference between the two line to line voltages is plotted on a linear scale. This spectrum shows that only a small difference in the line to line voltage occurs at the switching frequency when the new space vector modulation is used to control the four pole inverter. Except for a small difference at the frequency of the third harmonic, the two differential mode voltages are essentially the same over the rest of the frequency interval.

B. Three-dimensional space vector modulation

A new switching pattern can be also be developed for the three phase inverter which avoids the zero state. In this case one additional time, T_4, is defined to allow one more constraint to be applied to the system. The added constraint is selected to control the common mode voltage to zero. Equation (4) is replaced with:

$$\frac{T_s}{2} = T_1 + T_2 + T_3 + T_4 \tag{8}$$



(b)

Fig. 10 Spectra (0-100 kHz) of line to line voltage before the filter: (a) three phase inverter with old space vector modulator, (b) four phase inverter with new space vector modulator

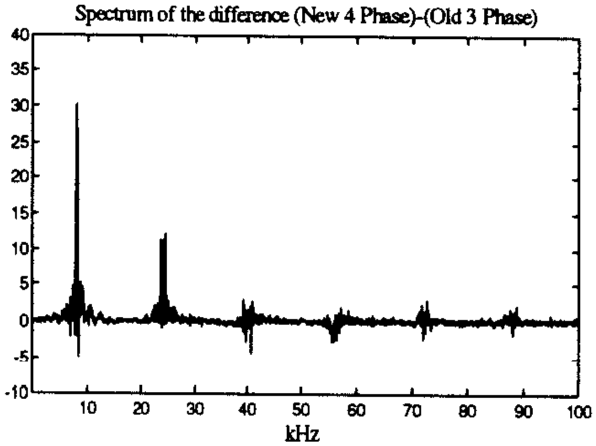


Fig. 11 Difference of the two spectra shown in Fig. 10: 'New-Old' space vector modulators (b)-(a)

Also equation (3) becomes:

$$\overline{V}_6T_1 + \overline{V}_1T_2 + \overline{V}_2T_3 + \overline{V}_3T_4 = \overline{V}_{ref}\frac{T_s}{2} \qquad (9)$$

The third equation needed in order to determine the four intervals is given by the zero axis equation. This equation is not typically used in traditional space vector modulation since the common mode voltage is not taken in account. This third equation can be obtained by projecting the space vectors onto the zero axis, because all the vectors are actually located in the three dimensional space *dq*0, while the traditional practice uses only their projection onto the *dq* plane. By including the zero axis in the modulation strategy the space vectors lay on a three-dimensional space instead of a plane [4]. This new space vector modulation strategy can be termed three dimensional space vector modulation.

By projecting the vector equation (9) on the axes *q*, *d* and 0, yields:.

$$V_{6q}T_1+V_{1q}T_2+V_{2q}T_3+V_{3q}T_4=V_{qref}\frac{T_s}{2} \qquad (10)$$

$$V_{6d}T_1+V_{1d}T_2+V_{2d}T_3+V_{3d}T_4=V_{dref}\frac{T_s}{2} \qquad (11)$$

$$V_{60}T_1+V_{10}T_2+V_{20}T_3+V_{30}T_4=0 \qquad (12)$$

where the common mode voltage has been forced to be zero ($V_{0ref} = 0$) in Eq. (12), and:

$$\begin{bmatrix} V_{xq} \\ V_{xd} \\ V_{x0} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (13)$$

where:

$$S_x = \pm\frac{V_{dc}}{2} \qquad (14)$$

Eq. (13) represents the typical *abc* to *qd*0 axes transformation. S_x represents the switching states for the three phases of the inverter (x=a,b,c). Note that the switching state of the fourth phase is always chosen to satisfy Eq. (2). Therefore when two top (bottom) and 1 bottom (top) switches are selected by the modulator to be turned on, in the fourth phase the bottom (top) switch is turned on.

By solving the set of four equations (8), (10)-(12) the four times T_1, T_2, T_3 and T_4 are computed and the switching pattern can be:

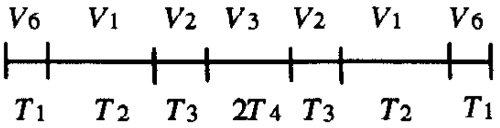


Fig. 12 Switching pattern for the three-dimensional space vector modulation strategy

In Figs. 13 and 14 is shown the common mode current, I_{ground}, produced by a four phase inverter controlled with the first space vector modulator presented in section A and the three-dimensional space vector modulation strategy respectively. The simulations are performed for a modulation index of 0.74, since the three dimensional space vector modulation is limited to a maximum modulation index of 0.75. Therefore the three dimensional space vector strategy gives better results then the first new space vector presented but limits the output voltage that can be produced by the four pole VSI. The performance of the two new space vector modulation strategies can be compared in terms of the differential mode voltage in Fig. 15.

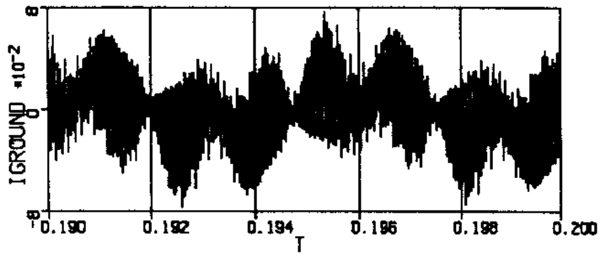


Fig. 13 Ground current in a four phase inverter controlled with the first space vector modulator

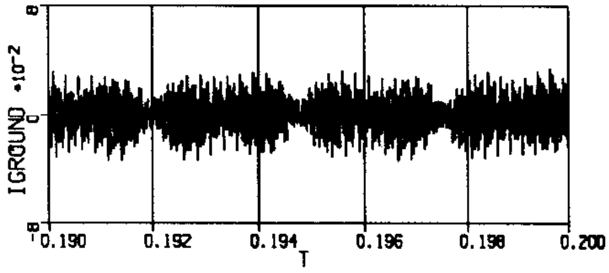


Fig. 14 Ground current in a four phase inverter controlled with the three dimensional space vector modulator

In Fig. 15 is shown the spectrum of the difference between output line to line voltage produced by a four phase inverter with the first and the three-dimensional space vector modulation strategies respectively. This picture shows that the differential mode performance of the three dimensional space vector modulation strategy are generally better then those of the first new space vector modulation technique.

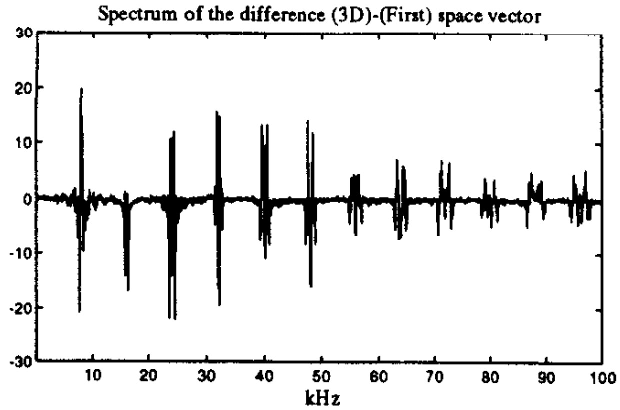


Fig. 15 Spectrum (0-100 kHz) of the difference between the line to line voltage before the filter in a four phase VSI controlled with first and 3-D space vector modulation

V. COMMON MODE VOLTAGE REDUCTION IN EXISTING THREE PHASE VSI

It is evident that the zero state produces the highest common average output voltage in three phase inverters, according to Eq. (1). This suggests that any modulation strategy which eliminates the zero state from the possible states of the converter reduces the common mode emission produced by a typical three phase inverter. The modulation strategies used to control a four pole inverter do not select the zero state in order to satisfy the constraint in Eq. (2). Therefore any modulation strategy used to control the four phase inverter helps reduce the common mode emission when used to control a traditional three phase inverter.

In this section the two space vector modulation strategies are applied to a typical three phase topology in order to show that they can reduce the common mode current circulating in the ground path of the inverter.

In Figs. 16 and 17 the simulated common mode current, I_{ground}, is plotted in the time domain for a three phase inverter controlled with the first and the three dimensional space vector modulation respectively.

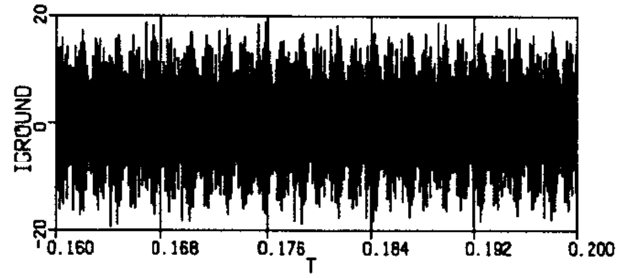


Fig. 16 Ground current in a three phase inverter controlled with the first new space vector modulation

By comparison with Fig. 8 it can be noted that the two ground currents are less than half of that produced by the same inverter controlled by a traditional space vector modulator. Like the four phase topology, the differential mode performance of the three phase inverter is slightly poorer than for typical three phase space vector modulation. However, no hardware changes are required to obtain the reduced common mode currents shown in Figs. 16 and 17.

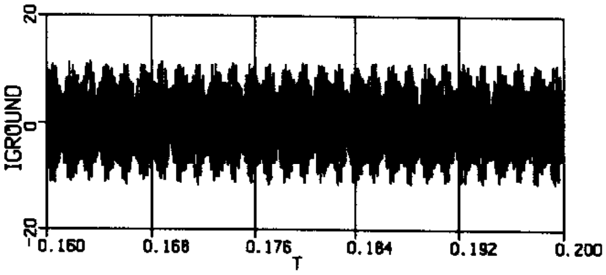


Fig. 17 Ground current in a three phase inverter controlled with the three dimensional space vector modulation

CONCLUSION

This paper tackles the common mode emission problem existing in multi phase voltage source inverters. The impact of the inverter control strategy is studied and two space vector modulation strategies are proposed for a four phase inverter topology with a three phase load to reduce the common mode voltage produced by the VSI.

These modulation strategies are proven to be very effective for four phase inverters. In addition they allow a reduction of 50% in the common mode voltage produced by a typical three phase inverter.

While the first new modulation strategy achieves any output voltage that can be produced by a typical VSI with a traditional space vector modulator, the three-dimensional strategy is limited to a maximum modulation index of 0.75. On the other hand the three dimensional strategy achieves better performance in terms of common mode voltage reduction and differential mode distortion.

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