AN IMPROVED MODULATION STRATEGY FOR A HYBRID MULTILEVEL INVERTER

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Abstract -- Multilevel cascaded and hybrid inverter systems conventionally use three level bipolar PWM for each individual inverter, with their carriers phase shifted to achieve maximum harmonic cancellation within each phase leg. This has been shown to give a harmonic performance equivalent to APOD modulation of a NPC multilevel inverter, when the switching frequencies are scaled to achieve the same number of overall switch transitions. In contrast, PD modulation of a NPC inverter is harmonically superior, because it places harmonic energy directly into the carrier harmonic for each phase leg, and relies on cancellation of this harmonic across phase legs as the line-to-line voltage is developed. Using this understanding, a new discontinuous modulation strategy is proposed for a hybrid inverter which achieves a similar level of improvement in line-to-line harmonics compared to conventional three level modulation of this type of inverter.

I. INTRODUCTION

Multilevel converters are increasingly being considered for high power applications because of their ability to operate at higher output voltages while producing lower levels of harmonic components in the switched output voltages. Two well known multilevel converter topologies are the Neutral Point Clamped (NPC) Inverter [1] shown in Figure 1 and the Cascaded inverter [2] shown in Figure 2.

The NPC inverter uses a series string of capacitors to subdivide a single high voltage DC bus into the required number of voltage levels, and each phase leg output can be switched to any one of these levels. In comparison the Cascaded inverter uses the series connection of a number of full bridge inverters to construct each multilevel phase leg. The main disadvantage of this topology is that each full bridge inverter requires its own isolated DC supply, which is generally achieved using a multiwinding low frequency transformer or high frequency DC to DC converters [3]. The need for these DC supplies has generally restricted the use of Cascaded inverters to the high power range of operation where several output voltage levels are needed and the Neutral Point Voltage balancing problem for a NPC inverter complicates the use of that structure. A further attraction of the Cascaded inverter is that the control and protection requirements of each bridge are modular [4].

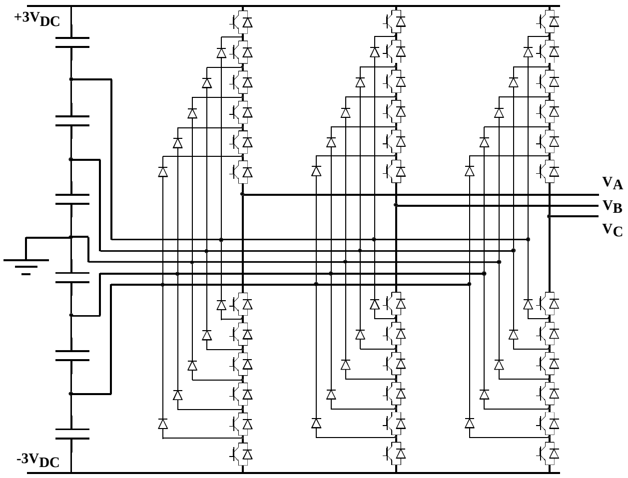

Figure 1 : Structure of a 7 Level Neutral Point Clamped (NPC) Inverter.

More recently, a new inverter topology (derived from the Cascaded structure) called the Hybrid inverter has been proposed, where the cascaded series inverters have different internal DC bus voltages, use different switching devices (IGCT's and IGBT's) and are modulated quite differently [5]. The advantage of this topology, shown in Figure 3, is a reduction in switch count (36 down to 24 devices for a 7 level inverter) and more effective usage of the natural switching speed and voltage blocking characteristics of the

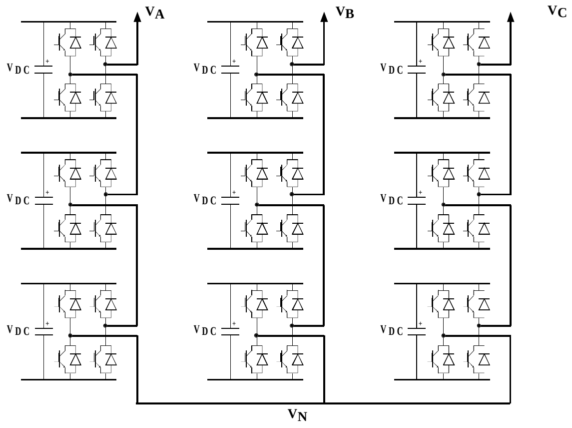

Figure 2 : Structure of a Seven Level Cascaded Inverter.

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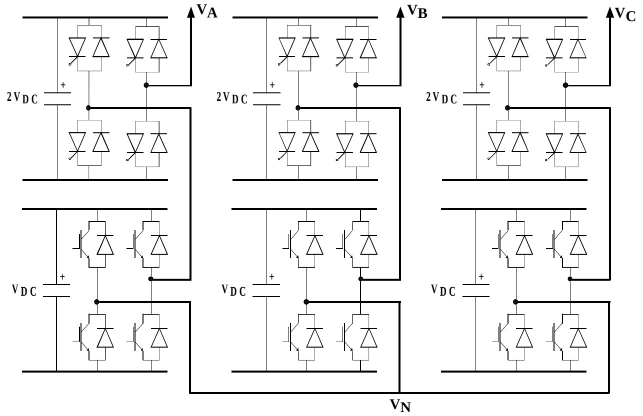

Figure 3 : Structure of a Seven Level Hybrid Inverter.

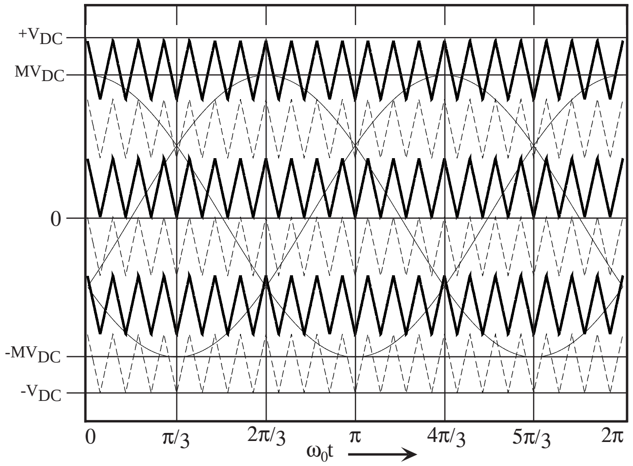

Figure 4 : Reference and Carrier Waveform arrangement for PD PWM of a 7 Level NPC inverter.

different types of power electronic devices that are required. Furthermore because the number of full bridge inverters required is reduced the design of the multiwinding transformer for the DC supplies is considerably simplified.

Modulation of a multilevel converter is quite challenging, and much of the reported research is based on somewhat heuristic investigations. For NPC multilevel inverters, most carrier based modulation strategies derive from disposition techniques developed by Carrara et al [6], where for an N level inverter, N-1 carriers of identical frequency and amplitude are arranged to occupy contiguous bands between $+V_{DC}$ and $-V_{DC}$. These carriers can be arranged in:

(i) Alternative Phase Opposition Disposition (APOD), where each carrier is phase shifted by 180^0 from its adjacent carriers.

(ii) Phase Opposition Disposition (POD) where the carriers above the reference zero point are out of phase with those below the zero point by 180^0.

(iii) Phase Disposition (PD) where all carriers are in phase.

Figure 4 shows the reference and carrier waveform arrangements necessary to achieve PD PWM for a seven level converter. It is known from previous work [6] [8] that the PD technique produces less harmonics on a line-to-line basis compared to the other two techniques because it puts harmonic energy directly into a common mode carrier component which cancels across the line-to-line outputs.

For Cascaded Inverters, the common modulation strategy is to use continuous three level PWM within each individual inverter, with phase shifted carriers between the cascaded inverters of each phase leg to achieve optimum harmonic cancellation within the phase leg [7]. Recent work [8] has shown that this modulation strategy achieves the same harmonic performance as the APOD technique for NPC inverters when the switching frequencies are normalised so as to achieve the same overall number of switching transitions per fundamental cycle. From this understanding, an improved modulation strategy for Cascaded inverters has been developed using a discontinuous three level PWM strategy with 180^0 phase shifted carriers within each full bridge inverter, which achieves the same harmonic performance on a line-to-line basis as does PD modulation for a NPC inverter.

Since the Hybrid inverter topology is derived from the Cascaded structure it is reasonable to expect that a similar situation exists for the Hybrid inverter. This paper confirms this expectation, firstly by showing that the Hybrid inverter with three level modulation of the PWM inverters, like the Cascaded inverter, does achieve a performance similar to the NPC inverter under APOD modulation, and then by proposing a discontinuous PWM strategy with 180^0 phase shifted carriers for the Hybrid converter, which achieves an improved harmonic performance similar to PD modulation of a NPC inverter.

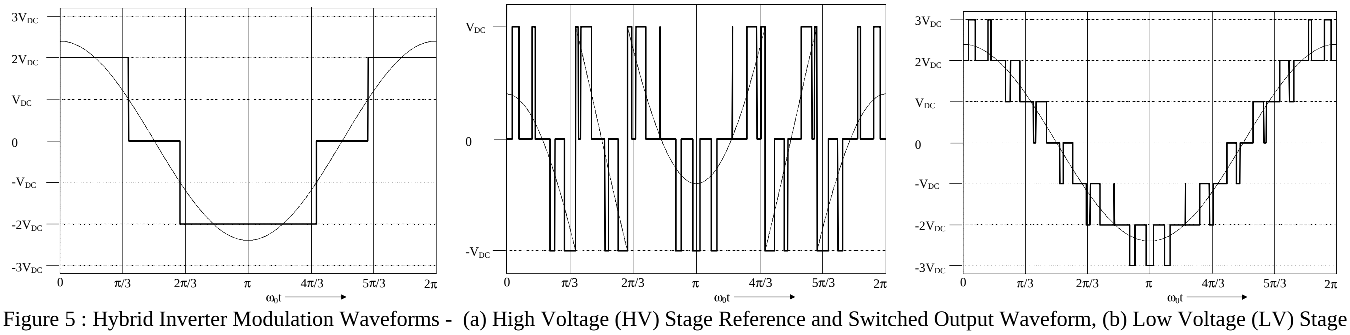

Figure 5 : Hybrid Inverter Modulation Waveforms - (a) High Voltage (HV) Stage Reference and Switched Output Waveform, (b) Low Voltage (LV) Stage Reference and Switched Output Waveform, (c) Hybrid Inverter Switched Output Waveform.

$$F(t)=\frac{A_{00}}{2}+\sum_{n=1}^{\infty}\left\{\begin{aligned}A_{0n}\cos(n\omega_o t)+\\ B_{0n}\sin(n\omega_o t)\end{aligned}\right\}+\sum_{m=1}^{\infty}\left\{\begin{aligned}A_{m0}\cos(m\omega_c t)+\\ B_{m0}\sin(m\omega_c t)\end{aligned}\right\}+\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n\neq 0}}^{\infty}\left\{\begin{aligned}A_{mn}\cos(m\omega_c t+n\omega_o t)+\\ B_{mn}\sin(m\omega_c t+n\omega_o t)\end{aligned}\right\} \qquad (1)$$

$$C_{mn}=A_{mn}+jB_{mn}=\frac{1}{2\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi}F(x,y)e^{j(mx+ny)}dxdy\ , \qquad x=\omega_c t,\ y=\omega_o t \qquad (2)$$

II. ANALYSIS OF MODULATION OF THE HYBRID MULTILEVEL INVERTER.

Figure 5 shows the reference and switched voltage waveforms for the previously published modulation strategy for a Hybrid multilevel inverter [5]. For each phase leg, the inverter consists of a High Voltage (HV) stage (based on IGCT's) in series with a Low Voltage (LV) stage (based on IGBT's). The HV stage is modulated with the required fundamental reference sine wave (maximum magnitude $3V_{DC}$) and switches high if the reference exceeds $+V_{DC}$, low if the reference is less than $-V_{DC}$ or otherwise produces 0V (Figure 5a). The LV reference waveform is formed by subtracting the HV stage output from the overall reference waveform. In this way the LV reference contains information about the harmonic content of the HV stage. So when the LV stage switched voltage is formed using conventional three level PWM (Figure 5b) the result is a waveform that contains the low frequency harmonic components of the HV stage voltage as well as conventional high frequency PWM sidebands. The result when the two switched waveforms are combined together is a seven level switched waveform as shown in Figure 5c.

The harmonic performance of this modulation strategy can be found using a two stage process where the spectra for the HV stage and the LV stage are determined separately and then added together.

The harmonic content of the HV stage can be found using conventional one dimensional Fourier analysis. This gives the straightforward result presented in (3a).

The spectral profile of the LV stage can then be found using the Double Fourier Series method of analysis. This technique, first applied to power electronic systems by Bowes [9] and later applied specifically to multilevel waveform synthesis by Carrara et al [6], resolves the switched waveform into a Double Fourier harmonic series by representing it as a two dimensional function of the carrier and reference waveforms as shown in (1). The harmonic coefficients of (1) are found by evaluating the double integral in (2), by identifying the regions in the (x,y) plane where the function F(x,y) is constant, and summing together the integral parts from each of these regions. This is illustrated in Figure 6(a) which shows a contour plot of F(x,y) for the LV PWM stage of the Hybrid converter.

For the Hybrid converter, the integral in (2) for the LV stage is solved (after considerable algebra) to yield the result shown in (3b). The overall Hybrid converter solution is then obtained by summing (3a) and (3b) together to make a complete phase leg, as shown in (3c) and then summing together two phase legs to become the line to line voltage solution, as shown in (3d).

A similar solution process can be used to obtain the analytic solution to the voltage spectra produced by a NPC inverter under any of the disposition modulation techniques. Figure 6(b) shows the constant F(x,y) contour plot for the seven level APOD PWM technique, which has a significantly more complex form than the Hybrid case. However, following the same solution process, a similar result for the phase leg voltage and line to line voltage can be obtained as shown in equations (4a) and (4b) respectively.

Equations (3) and (4) show a strong similarity between the modulation of the Hybrid inverter under the continuous three level PWM strategy and the modulation of a NPC inverter under the APOD PWM strategy. In fact the only significant

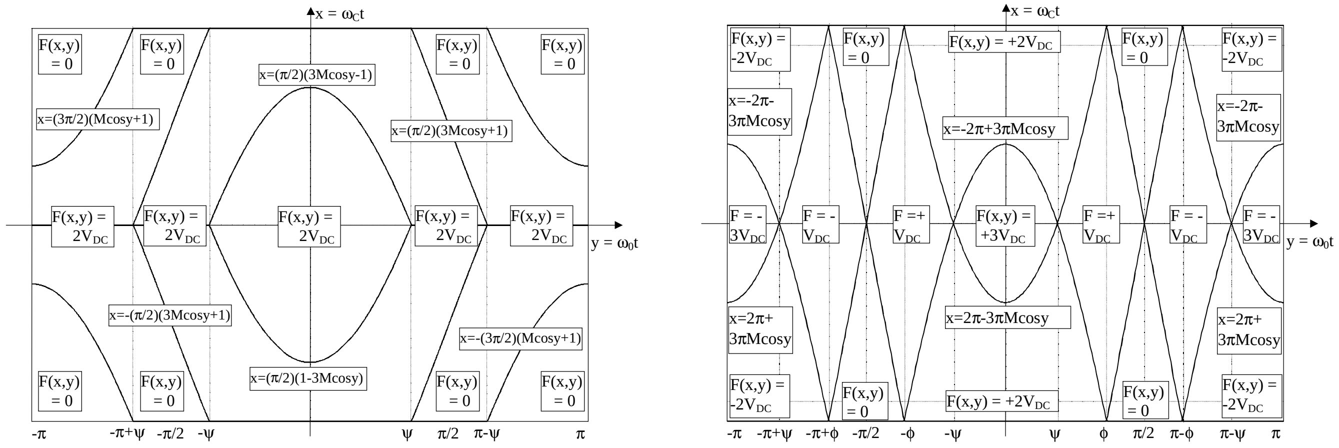

Figure 6 : Contour Plot of F(x,y) for (a) LV Stage, Seven Level Hybrid Inverter (b) Seven Level NPC inverter - APOD PWM.

$$V_{HV} = \frac{8V_{DC}}{\pi}\sum_{n=0}^{\infty}\left[\frac{1}{(2n+1)}\sin\left((2n+1)\cos^{-1}\left(\frac{1}{3M}\right)\right)\cos((2n+1)\omega_0 t)\right] \tag{3a}$$

$$\begin{aligned} V_{LV} = 3MV_{DC}\cos(\omega_0 t) - \frac{8V_{DC}}{\pi}\sum_{n=0}^{\infty}\left\{\frac{1}{2n+1}\sin\left((2n+1)\cos^{-1}\left(\frac{1}{3M}\right)\right)\cos((2n+1)\omega_0 t)\right\} \\ + \frac{2V_{DC}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n=0}}^{\infty}\left\{\frac{1}{m}\cos((m+n+1)\pi)J_{2n-1}(3m\pi M)\cos(2m\omega_C t + (2n-1)\omega_0 t)\right\} \end{aligned} \tag{3b}$$

$$V_{HYB\_AN} = 3MV_{DC}\cos(\omega_0 t) + \frac{2V_{DC}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n=0}}^{\infty}\left\{\frac{1}{m}J_{2n-1}(3m\pi M)\cos((m+n+1)\pi)\cos(2m\omega_C t + (2n-1)\omega_0 t)\right\} \tag{3c}$$

$$V_{HYB\_AB} = 3\sqrt{3}MV_{DC}\cos\left(\omega_0 t + \frac{\pi}{6}\right) + \frac{4V_{DC}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n=0}}^{\infty}\left\{\frac{1}{m}J_{2n-1}(3m\pi M)\cos((m+n)\pi)\sin\left((2n-1)\frac{\pi}{3}\right)\sin\left(\begin{matrix}2m\omega_C t + \\ (2n-1)\left(\omega_0 t - \frac{\pi}{3}\right)\end{matrix}\right)\right\} \tag{3d}$$

Equation 3 : Analytic Solution for the Voltage Spectra for a Hybrid Inverter with a continuous three level PWM strategy.
(a) HV Stage Spectra (b) LV Stage Spectra (c) Hybrid Phase Leg Voltage Spectra (d) Hybrid Line-to-Line Voltage Spectra..

difference is that for the NPC inverter the first set of sideband harmonics are centered about the carrier frequency, while for the Hybrid inverter these harmonics appear about the second multiple of the carrier. However, if the carrier frequencies are adjusted so that each scheme produces the same number of overall switch transitions per fundamental cycle then the spectra become the same, which confirms that an APOD equivalent modulation technique is being implemented on the Hybrid inverter. Figures 10 through 13 show the analytic switched voltage spectra for a NPC inverter under APOD PWM and a Hybrid inverter under continuous three level PWM with carrier frequencies normalised to achieve the same number of overall switch transitions. A comparison of these figures confirms that the same spectral performance has been achieved in both cases.

It should be noted in passing that there is one minor difference between equations (3) and (4) in terms of the sign of the sidebands. This difference results from different placement of the active states within the carrier interval for the two modulation strategies. Theoretically this difference could slightly affect sideband interactions between carrier sets, but in practice the effect is negligible for pulse ratios greater than 10.

III. PHASE DISPOSITION (PD) MODULATION FOR HYBRID INVERTERS.

Since it is known from previous work [6] that the PD technique is the harmonically superior modulation strategy for NPC inverters, the question then becomes how to implement a similar strategy for the Hybrid inverter. The key to achieving this objective comes from analysis of the spectrum of the phase voltage for a NPC inverter under PD modulation (Figure 16), where it can be seen that the most significant harmonic in the phase voltage is the first carrier component. This is in sharp contrast to APOD modulation which has only carrier sideband components. The implication of this observation is that PD modulation places significant harmonic energy into a direct carrier component and relies on cancellation of this component (amongst others) between phases when the line to line voltage is formed, as shown in Figure 17. So to achieve the equivalent of PD modulation for a Hybrid inverter, a carrier component should be retained in the phase leg voltage spectrum.

It is well known for single phase inverters that a carrier component is retained in the output voltage when the carriers for each phase leg have a 180^0 phase shift (i.e. two level modulation). However, the harmonic sidebands of two level

$$V_{APOD\_AN}(t) = 3MV_{DC}\cos(\omega_0 t) + \frac{2V_{DC}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n=0}}^{\infty}\left\{\frac{1}{m}J_{2n-1}(3m\pi M)\cos((n+1)\pi)\cos(m\omega_C t + (2n-1)\omega_0 t)\right\} \tag{4a}$$

$$V_{APOD\_AB}(t) = 3\sqrt{3}MV_{DC}\cos\left(\omega_0 t - \frac{\pi}{6}\right) + \frac{4V_{DC}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty\\ n=0}}^{\infty}\left\{\frac{1}{m}J_{2n-1}(3m\pi M)\cos(n\pi)\sin\left((2n-1)\frac{\pi}{3}\right)\sin\left(\begin{matrix}m\omega_C t + \\ (2n-1)\left(\omega_0 t - \frac{\pi}{3}\right)\end{matrix}\right)\right\} \tag{4b}$$

Equation 4 : Analytic Solution for the Voltage Spectra for a 7 Level NPC Inverter under APOD PWM
(a) Phase Leg Voltage Spectra (b) Line to Line Voltage Spectra.

modulation occur around the carrier frequency, rather than around the double carrier frequency as occurs for three level modulation. So the switching frequency benefit of three level modulation is lost, unless the reference waveform is modified so as to achieve discontinuous modulation. (Discontinuous modulation allows the carrier frequency to be doubled to retain the same switching frequency per fundamental cycle) Of course, as a consequence, the switching losses for any one switch are condensed into only part of the fundamental cycle, but this is very similar to the way a NPC inverter operates under any of the disposition modulation techniques.

Applying these concepts to the Hybrid inverter suggests that the LV stage reference waveform must be modified to achieve discontinuous modulation. Figure 7(a) shows the reference and carrier waveform arrangements used for the the previous continuous three level LV stage PWM, while Figure 7(b) shows the necessary modifications required to achieve discontinuous three level PWM. For continuous PWM, the reference for the second phase leg in the LV full bridge inverter is simply the inverse of the reference waveform for the first phase leg. For the discontinuous case, the two reference waveforms are arranged so that whenever a positive bridge output is required, the first phase leg is PWM modulated and the second phase leg is held to the negative rail, while whenever a negative bridge output is required, the first phase leg is held to the negative rail and the second phase leg is PWM modulated.

Figures 18 and 19 respectively show the simulated phase leg and line voltage spectra of the Hybrid inverter under this form of discontinuous modulation. A comparison of these spectra with those of Figures 16 and 17 shows that the discontinuous PWM technique for Hybrid inverters has achieved equivalent harmonic performance to PD modulation of an NPC inverter. Furthermore, this result has been achieved without requiring co-ordinated switching across all three phase legs of the hybrid inverter, hence maintaining the modularity of control that is seen as an advantage of the Cascaded inverter type topologies.

IV. EXPERIMENTAL IMPLEMENTATION.

In principle the Hybrid inverter topology uses different switching devices in the HV and LV stages. However, for simplicity, a lower voltage system was constructed for this investigation which used IGBT based inverters for both the LV and the HV stages.

The experimental Hybrid inverter system comprised two single phase inverters per phase leg, with two phase legs only being constructed. Each phase leg was controlled using a TMS320C240 DSP micro controller. (It is commented that this DSP does not support 180^0 phase shifted carriers with the PWM outputs that are available, so this requirement was implemented for the LV stage by enabling one set of gate signals as active high and the second set as active low. The reference waveform for the active low gate signals was then inverted, to achieve an effective 180^0 carrier phase shift.)

Figures 8 and 9 show the switched output voltages and filtered load currents for the Hybrid inverter under both the continuous three level PWM strategy and the new discontinuous three level PWM method. Figures 14, 15 and 20, 21 show the experimental spectra for the phase and line-to-line voltages for the two modulation approaches respectively. These figures can be directly compared with the analytical and simulated spectra shown in Figures 10 - 13 and 16 – 19. From these results it can clearly be seen that the discontinuous PWM method has a significant harmonic improvement when compared to the continuous PWM and achieves the same performance as a seven level NPC inverter operating under PD modulation.

Close examination of Figures 8 and 9 also reveals a small anomaly in the switched waveform - a spurious pulse in the switched phase voltage that occurs each time the HV stage makes a transition (i.e. four times per cycle). These pulses arise from the requirement that when the HV stage makes a transition, a corresponding LV transition must also occur exactly at the same time. If these transitions do not occur together then a pulse equal to the size of the HV DC bus results for a short time.

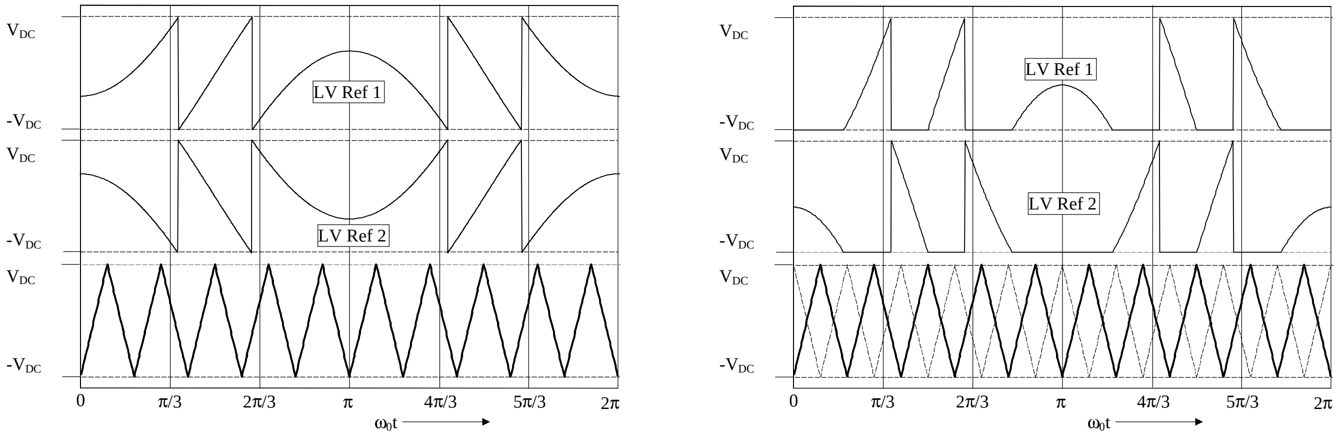

Figure 7 : Hybrid Inverter modulation, Reference and Carrier Waveform Arrangement – LV Stage.
(a) Conventional Modulation (b) Bipolar Discontinuous PWM.

Under detailed examination the width of the pulses were found to be 3μsec, which is the exact interval of the dead time period for the inverters. So the pulses arise because of dead time preventing the simultaneous transition of the HV and LV inverters.

This has significant implications for a Hybrid converter constructed from IGCT's and IGBT's, since the two device types will have different dead time requirements, and different rise times. Determining the exact time at which the HV stage must switch to minimise these pulses may be quite complex, and is still unresolved at this point.

V. SUMMARY.

Continuous three level modulation of the individual inverters in multilevel Hybrid inverter systems has been shown to achieve an equivalent harmonic performance to APOD modulation of a NPC multilevel inverter, when the switching frequencies are scaled to achieve the same number of overall switch transitions. However, it is known from previous work that PD modulation of a NPC inverter is harmonically superior. Analysis of this modulation strategy has shown that its superiority derives from the fact that it places harmonic energy directly in the carrier harmonic for each phase leg, and then relies on cancellation of this harmonic across phase legs as the line-to-line voltage is developed. Based on this result, a discontinuous modulation strategy has been developed for Hybrid inverters which achieves the same improvement in line-to-line harmonics compared to continuous three level modulation of the inverter. Theoretical and experimental results confirming these findings have been presented.

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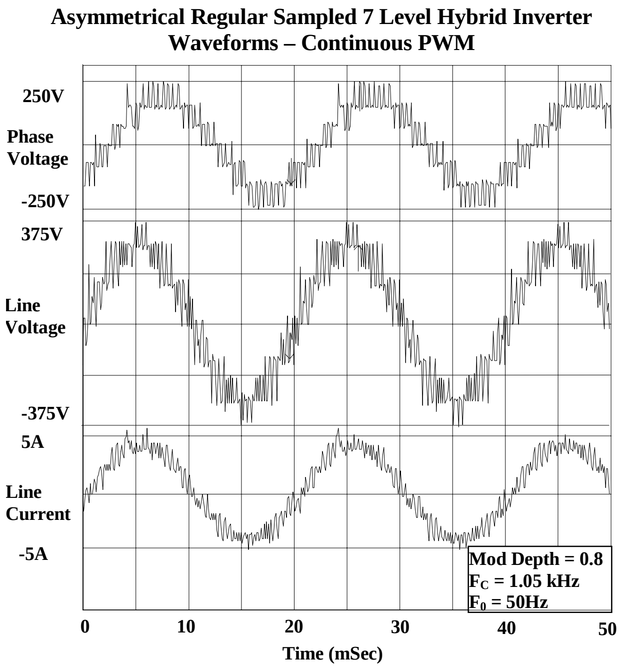

Figure 8 : Hybrid Inverter Experimental Switched Waveforms - Continuous Three Level PWM.

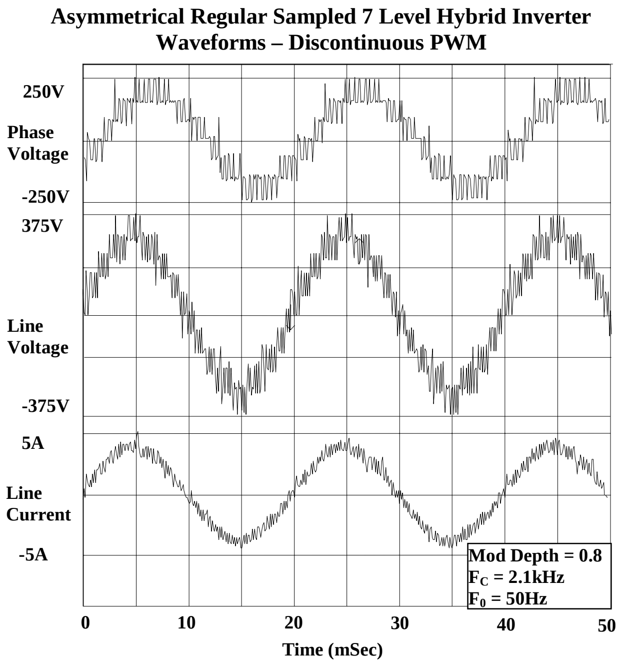

Figure 9 : Hybrid Inverter Experimental Switched Waveforms - Discontinuous Three Level PWM.

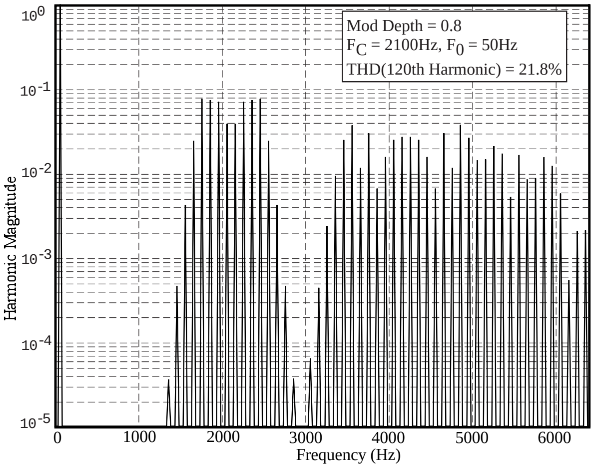

Figure 10 : NPC Inverter, APOD PWM - Analytical Phase Leg Voltage Spectrum.

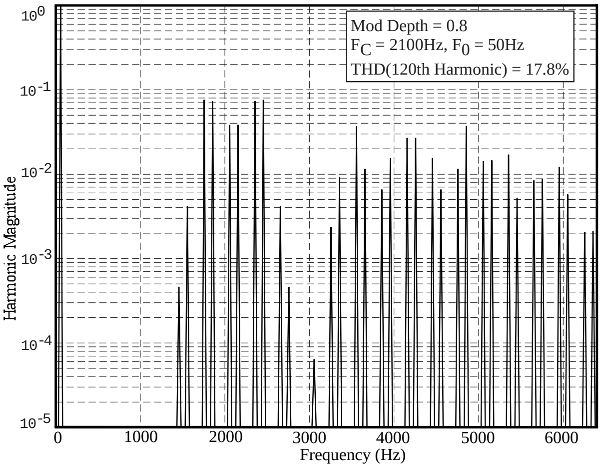

Figure 11 : NPC Inverter, APOD PWM - Analytical Line-to-Line Voltage Spectrum.

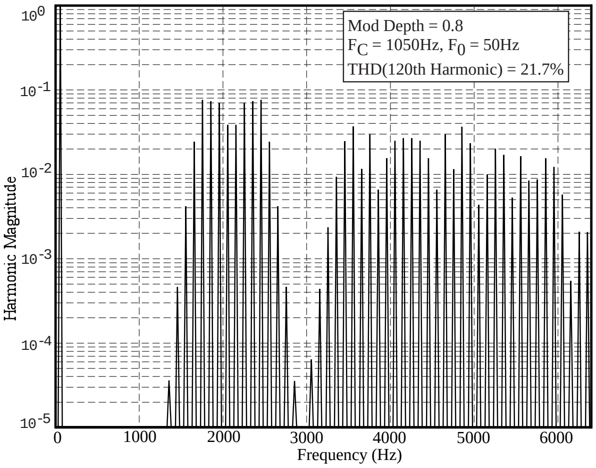

Figure 12 : Hybrid Inverter, Continuous Three Level PWM - Analytical Phase Leg Voltage Spectrum.

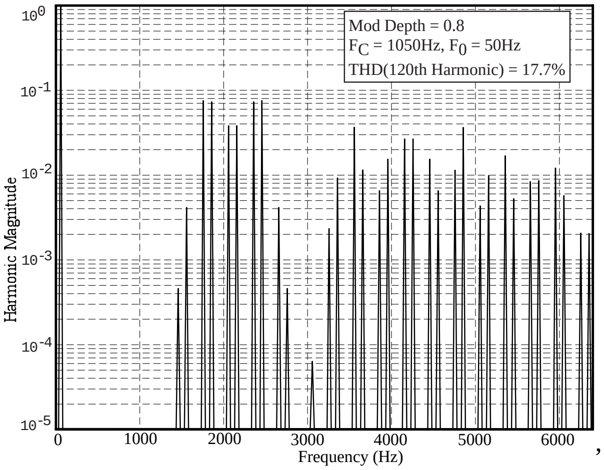

Figure 13 : Hybrid Inverter, Continuous Three Level PWM - Analytical Line-to-Line Voltage Spectrum.

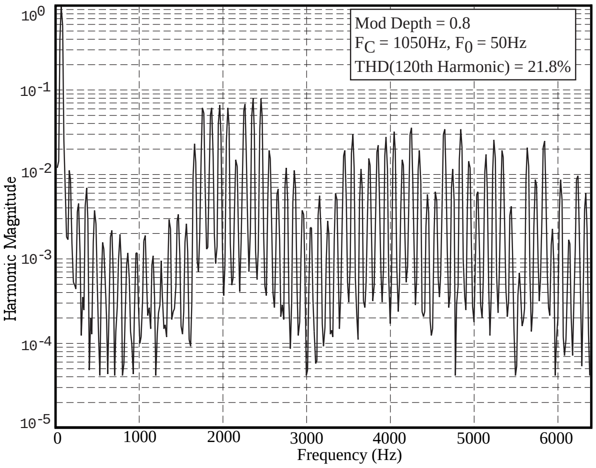

Figure 14 : Hybrid Inverter, Continuous PWM - Experimental Phase Leg Voltage Spectrum.

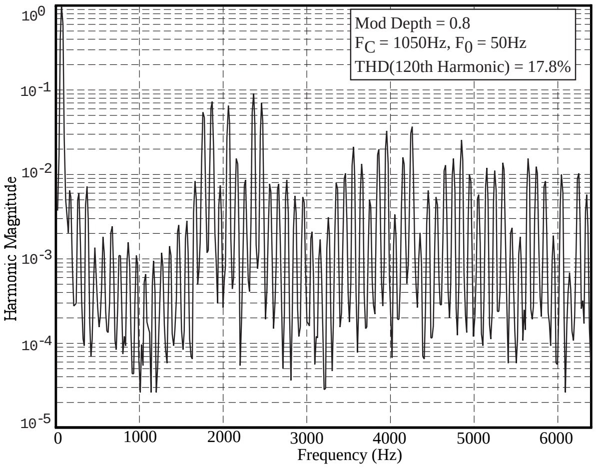

Figure 15 : Hybrid Inverter, Continuous Three Level PWM - Experimental Line-to-Line Voltage Spectrum.

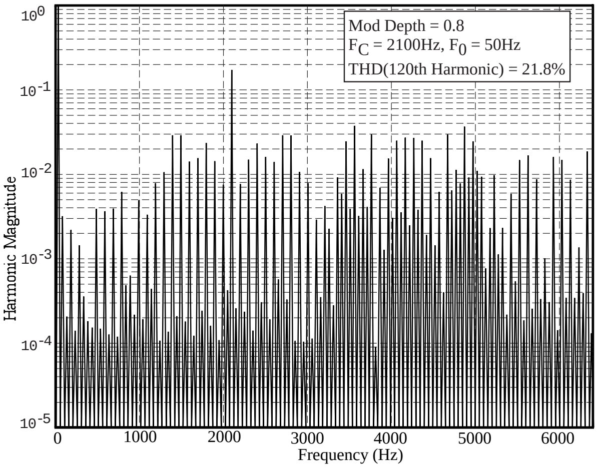

Figure 16 : NPC Inverter, PD PWM - Simulated Phase Leg Voltage Spectrum.

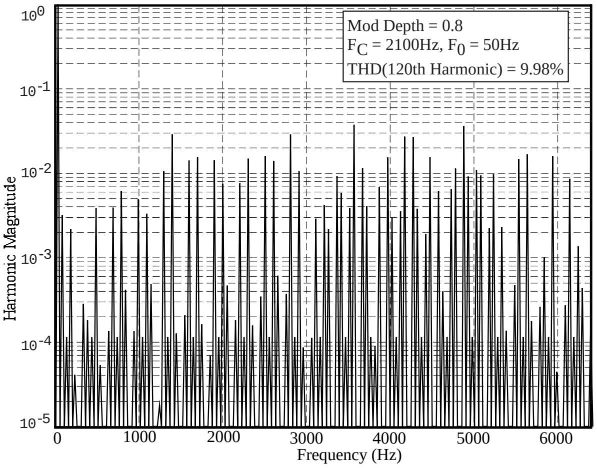

Figure 17 : NPC Inverter, PD PWM - Simulated Line-to-Line Voltage Spectrum.

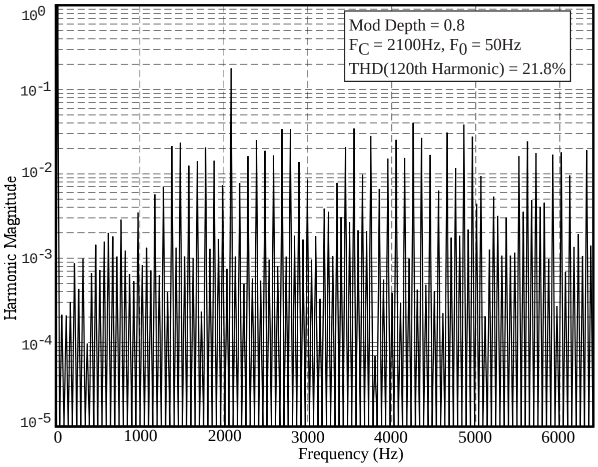

Figure 18 : Hybrid Inverter, Discontinuous Three Level PWM - Simulated Phase Leg Voltage Spectrum.

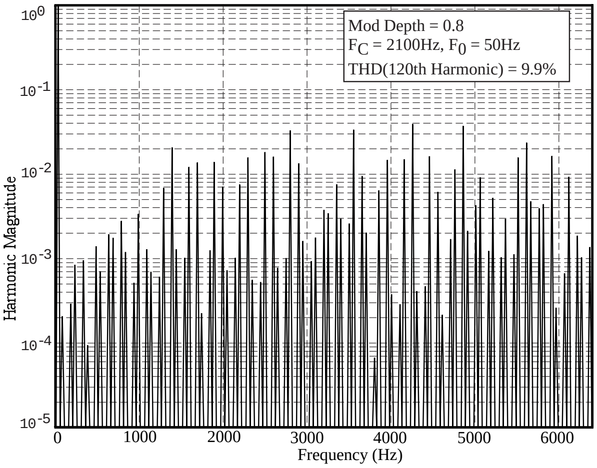

Figure 19 : Hybrid Inverter, Discontinuous Three Level PWM - Simulated Line-to-Line Voltage Spectrum.

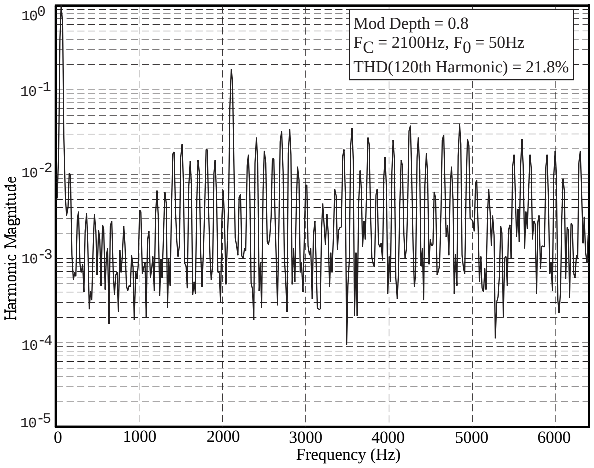

Figure 20 : Hybrid Inverter, Discontinuous Three Level PWM - Experimental Phase Leg Voltage Spectrum.

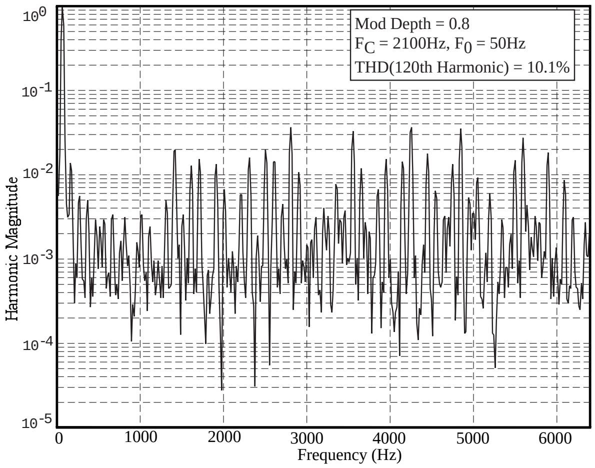

Figure 21 : Hybrid Inverter, Discontinuous Three Level PWM - Experimental Line-to-Line Voltage Spectrum.