



# **An Over-modulation Algorithm for Carrier Based Space Vector PWM Inverters**

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**ABSTRACT:** Carrier based Space Vector Pulse Width Modulation (SVPWM) has the advantage of ease of implementation and lower processor overheads as no timing calculation is required. Appropriate reference signals are generated, which, on comparison with a triangular carrier, gives the gating pulses for the semiconductor switches. However, just as in the case of switching time calculation, the amplitude of the reference waveform does not bear a linear relationship to the output fundamental voltage in the over-modulation region. This paper discusses a method to generate a modified reference signal so that a linear relationship exists between the commanded modulation index and the actual fundamental output over the entire range of modulation index.

**KEYWORDS :**Linear modulation, Carrier based SVPWM, Reference pre-processor, Modified look-up-table.

## **I. INTRODUCTION**

The output fundamental voltage has to be varied in inverter fed AC drive systems depending on the speed requirements. This is facilitated by varying the modulation index of the inverter based on the control algorithm. The modulation index can be varied from the lowest value to that value of fundamental voltage available in the six-step operation mode. It is desirable to have a linear relationship between the modulation index and the fundamental component of output voltage. The modulation index determines the switching times for the different inverter states in conventional space vector modulation, and the magnitude of the reference voltage in carrier based PWM techniques. The fundamental component of the inverter output voltage is directly proportional to the modulation index, in either case, only in the linear modulation range. Beyond the linear range, increasing modulation index does not proportionately increase the output fundamental component. The exact relation between fundamental and the amplitude of the reference also depends on the ratio of carrier to fundamental frequencies in carrier based schemes. If the carrier is of sufficiently high frequency, then it can be assumed that the output voltage and reference signal are directly related. In this paper, carrier based implementation is discussed, for both sinusoidal pulse width modulation (SPWM) and conventional space vector pulse with modulation (CSVPWM).

## **II. MODULATION ALGORITHMS**

The fundamental component of the output voltage of an inverter can be controlled in carrier based algorithms by varying the magnitude of the reference signal vis-a-vis the fixed amplitude carrier signal. A figure of quantifying the output is the modulation index ( $MI$ ). The modulation index has been variously defined as the ratio of the normalized fundamental output voltage to the normalized fundamental output voltage in six step operation ( $MI \leq 1$ ), and the ratio of the peak of the reference signal to the peak of the carrier. In this paper, the modulation index is taken as the ratio of normalized fundamental output voltage to peak of carrier. The normalized fundamental output voltage is the ratio of output fundamental to half the DC link voltage. The maximum  $MI$  is then  $\frac{4}{\pi}$

A scheme for linearising the output fundamental voltage has been discussed in [1], [2]. In both these papers, the output has been computed based on the locus of the voltage vector in the voltage space vector plane.. An analysis of the output

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or gain for different modulation schemes has been performed in [3]. The operation of the inverter under continuous linear mode has been described in [4]. A Fourier analysis of SVM inverters in the over-modulation range has been described in [5]. An implementation of the SVPWM is described in [6] where modified timings are used, an equivalent implementation of conventional SVPWM based on carrier comparison is discussed in [7]. Relationship Between Space-Vector Modulation and Three-Phase Carrier-Based PWM[8]. Different algorithms are also discussed for multi-level inverters where several topologies are discussed, using three-phase reference signals and level-shifted carriers of various dispositions.[9], [10].

This paper analyses the fundamental component of the output for both SPWM and SVPWM in the time domain by evaluating the relevant Fourier component of the reference signal whose amplitude is between the positive and negative peaks of the reference signal. The paper then suggests a modification of the reference so that a linear relationship exists between the commanded modulation index and the fundamental component of the output voltage.

### III. SINUSOIDAL PULSE WIDTH MODULATION

In sinusoidal pulse width modulation (SPWM), a carrier of switching frequency is compared with a sinusoidal reference signal to generate the gating pulses. The normalized carrier is assumed to vary over a magnitude of unity in both positive and negative direction. The average output pole voltage of the inverter depends on the peak amplitude of the modulating and carrier signals. For peak of modulating signal less than unity, the output pole voltage is proportional to the peak of modulating signal and the DC link voltage. The modulation index is defined as the ratio of the peak fundamental output voltage  $V_f$  to the peak fundamental output when the amplitude of reference is equal to the amplitude of the carrier. In the linear modulation region, the peak amplitude  $V_m$  of the reference is less than unity. If the magnitude of the reference voltage exceeds unity, that part of the reference above unit magnitude does not result in the generation of any switching pulses. The peak amplitude of the reference effectively is then unity, which is also the peak of the carrier. This means that all values of reference above unit magnitude is clipped as in Fig.1. The figure also indicates a phase angle  $\alpha$  at which a reference in the over-modulation region crosses unity. Although the reference has a peak amplitude of  $V_m$ , the output fundamental will be lower than this value because of the clipping. The peak of the output fundamental can be determined by determining the Fourier coefficient of the fundamental component of the clipped reference.

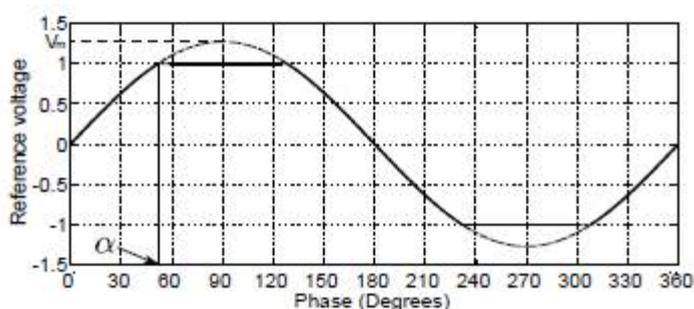


Fig. 1: Limiting of reference voltage in over-modulation region

In the over-modulation region therefore, the modulating signal can be defined as:

$$f(\omega t) = \begin{cases} V_m \sin \omega t, & 0 \leq \omega t \leq \alpha \\ 1 & , \alpha \leq \omega t \leq \frac{\pi}{2} \end{cases} \quad (1)$$

The fundamental component of the function above can be obtained by taking the Fourier series, and, because of symmetry, the integration needs to be done only for quarter cycle.



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$$V_1 = \frac{4}{\pi} \left[ \int_0^\alpha V_m \sin^2(\omega t) d\omega t + \int_\alpha^{\frac{\pi}{2}} \sin(\omega t) d\omega t \right] \quad (2)$$

$$= \frac{4}{\pi} \left[ V_m \left( \frac{\alpha}{2} - \frac{\sin 2\alpha}{4} \right) + \cos \alpha \right] \quad (3)$$

The value of  $\alpha$  can be determined from the reference voltage waveform as  $V_m \sin \alpha = 1$ . Substituting for  $V_m$  in the above equation, the magnitude of the fundamental component can be expressed as:

$$V_1 = \frac{2}{\pi} \left[ \frac{\alpha}{\sin \alpha} + \cos \alpha \right] \quad (4)$$

The maximum value of fundamental occurs at  $\alpha = 0$  for which equivalently, the modulation index become the theoretical maximum of  $\frac{4}{\pi}$  realizing that the first term in the braces is the sinc function. A plot of the variation of the fundamental with the angle  $\alpha$  is shown in Fig.2.

Although determining the value of  $\alpha$  to determine peak of reference voltage requires solving the transcendental equation, alternate ways of implementation are possible. Since modern day processors are extremely fast, a comparison operation can be performed to determine the value of intersection angle for a given fundamental voltage required. The angle is ramped up from zero in increments. On a match of the function with the desired fundamental value, the value of alpha is the angle at which the match occurred. The required reference voltage peak amplitude is then determined by evaluating the sine and cosine of this intersection angle from a sine look-up-table. The search algorithm can be optimized further since the value of the function is monotonic with respect to the intersection angle.

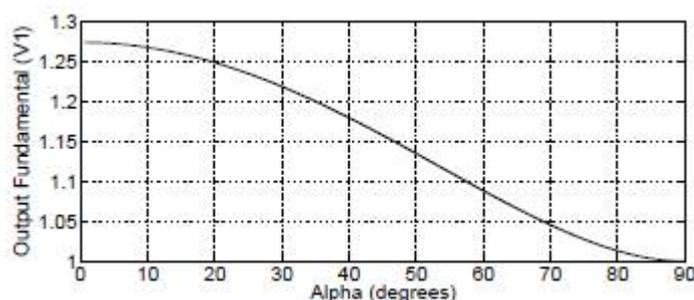


Fig. 2. Output fundamental versus \_ SPWM

Another implementation can be to predefine a look-up table that appropriately scales the peak of the reference fundamental as a function of the desired output fundamental in the over-modulation region. The relation between the peak reference and the peak fundamental output is indicated in Fig.3. It can be seen that the peak of reference signal tends to be infinite as the required output fundamental approaches the maximum possible value. This is consistent with the reference having to be a square wave for maximum output fundamental. In implementation a small constant value is added to the denominator to preclude a division by zero.

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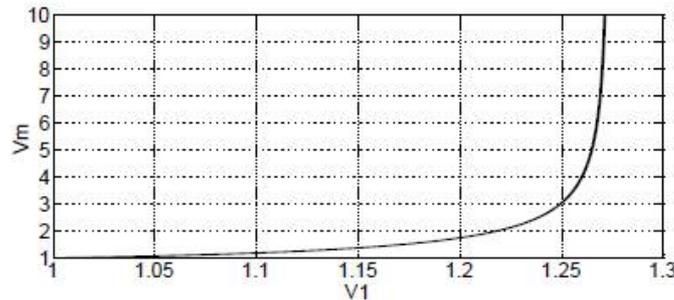
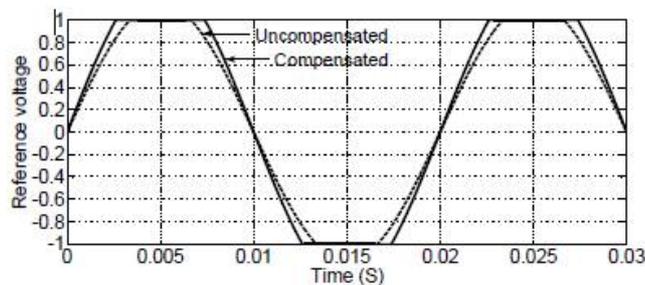


Fig. 3. Peak reference fundamental versus peak output fundamental

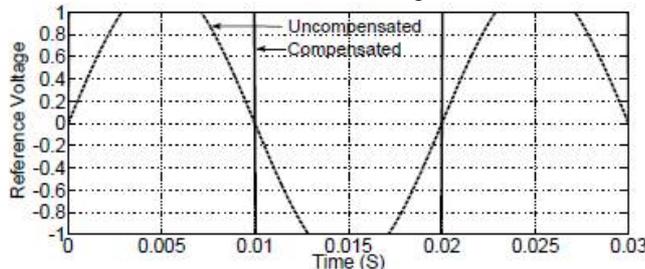
The reference fundamental thus has to be corrected in the over-modulation region to compensate for the loss of output fundamental because of the reference being clipped to the peak of the carrier. Fig.4 shows the compensated and uncompensated reference voltage wave-forms for two different values of modulation index.

## IV. SPACE VECTOR PULSE WIDTH MODULATION

SVPWM increases the range of linear modulation by adding a common mode to the three phase reference signals. This is facilitated by altering the switching times so that the effective time is positioned in the middle of the switching period or by a carrier based PWM scheme wherein a common mode voltage signal is added to the reference signals of the three phases. Effectively, the two zero states are applied for equal duration in either case.



(a) Over-modulation region



(b) Six-step mode

Fig. 4. Compensated and Uncompensated reference signals (SPWM)

The three phase reference voltages can be re-designated as  $V_{max}$ ,  $V_{mid}$  and  $V_{min}$  depending on their instantaneous values. Then, for equal zero state times at any instant, a common voltage is added to all three phase reference signals and the following equation must be satisfied:

$$1 - (V_{max} + V_{cm}) = (V_{min} + V_{cm}) - (-1) \text{ mid from which } V_{cm} = \frac{V}{2}$$

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For  $0 \leq \omega t \leq \frac{\pi}{6}$  middle valued signal is that of the 'a' phase and adding half of this to the same phase signal gives the 'a' phase reference signal for this interval. For  $\frac{\pi}{6} \leq \omega t \leq \frac{\pi}{2}$  the middle valued signal is that of the 'c' phase and so thereference signal is sum of the 'a' phase signal and the 'c' phase signal.

The function can thus be defined as:

$$\begin{cases} \frac{3}{2} V_m \sin(\omega t) & \left| 0 \leq \omega t \leq \frac{\pi}{6} \right| \\ \frac{3}{4} V_m \sin(\omega t) + \frac{\sqrt{3}}{4} V_m \cos(\omega t) & \left| \frac{\pi}{6} \leq \omega t \leq \frac{\pi}{2} \right| \end{cases} \quad (5)$$

This modulating signal is compared with a triangular carrier whose normalized amplitude can be considered to be unity as in the case of the sinusoidal pulse width modulation. The reference signal so generated has a common mode component present in the phase voltages, but do not appear in the line to line voltages. Using this reference instead of a sinusoidal signal also increases the range of linear modulation compared to the sinusoidal PWM. This is because the peak amplitude of the reference has been reduced with the addition of the common mode, thereby giving the option of further increasing the fundamental component before over-modulation begins.

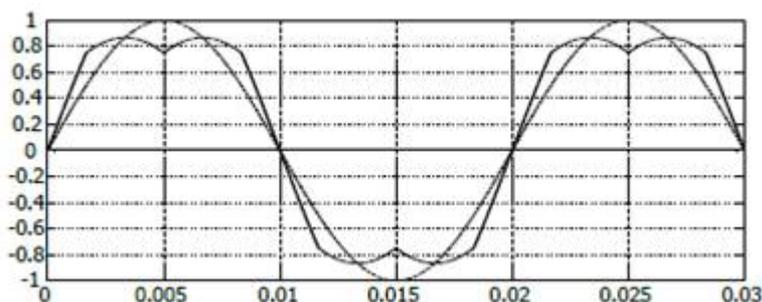


Fig. 5. Fundamental and modified with common mode

*phase angle at peak of reference and maximum linear modulation:* The reference signal generated in Eq. 5 is plotted in Fig.5 with the fundamental also shown. The second term in the above equation has a higher magnitude than the first, and the maximum value of the reference can be determined by differentiating the above with respect to  $\omega t$  and equating

to zero. The phase angle then turns out to be  $\frac{\pi}{3}$  and the maximum value of fundamental when the magnitude of the reference signal is unity at an angle of  $\omega t = \frac{\pi}{3}$  is  $\frac{2}{\sqrt{3}}$ . Thus it can be seen that by employing SVPWM, the range of linear modulation has increased by around 15% compared to the sinusoidal PWM whose peak phase fundamental is unity.

*Symmetry about  $\frac{\pi}{3}$ :* The second term in the above function represents the modulating signal for  $\frac{\pi}{6} \leq \omega t \leq \frac{\pi}{2}$ . This term can be shown to be symmetric about  $\omega t = \frac{\pi}{3}$  by evaluating it for  $\omega t = (\frac{\pi}{3} - \alpha)$  and  $\omega t = (\frac{\pi}{3} + \alpha)$ ,  $\alpha$  representing a shift to either side as depicted in Fig.6. The term evaluates to the same in either case, proving the symmetry.

### A. Regions of modulation

Depending on the modulation index, the modulation can be categorized into three distinct regions.

*Linear modulation:* For  $m \leq \frac{2}{\sqrt{3}}$  the inverter is operating in the linear modulation region, and the fundamental output voltage increases linearly as the reference amplitude is increased.

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Over-modulation region 1: As the amplitude of the reference is further increased ( $m \leq \frac{2}{\sqrt{3}}$ ) the modulation is nonlinear.

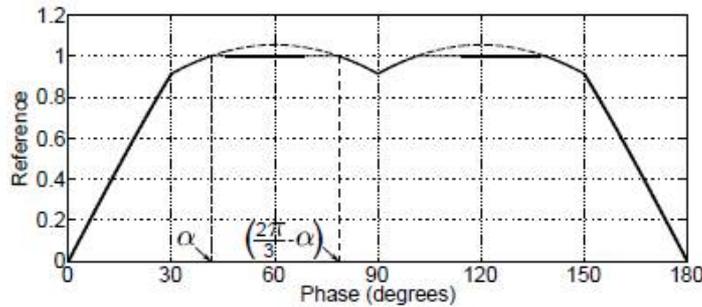


Fig. 6. Clipped reference signal and angle  $\alpha$  in over-modulation region 1

The fundamental output of the inverter is less than the fundamental component of the modulating signal, and this is evident in the clipping of the reference at the extreme values where the reference exceeds  $\pm 1$  as can be seen in Fig.6. This over-modulation region can be subdivided into two regions. The first region corresponds to that range of modulation index for which the reference is cut twice by the extreme of the carrier. The magnitude of fundamental output has to be determined by evaluating the Fourier coefficient of the fundamental. The output waveform can be defined in this region as

$$\left\{ \begin{array}{ll} \frac{3}{2}V_m \sin(\omega t) & 0 \leq \omega t \leq \frac{\pi}{6} \\ \frac{3}{4}V_m \sin(\omega t) + \frac{\sqrt{3}}{4}V_m \cos(\omega t) & \frac{\pi}{6} \leq \omega t \leq \alpha \\ 1 & \alpha \leq \omega t \leq \left(\frac{2\pi}{3} - \alpha\right) \\ \frac{3}{4}V_m \sin(\omega t) + \frac{\sqrt{3}}{4}V_m \cos(\omega t) & \left(\frac{2\pi}{3} - \alpha\right) \leq \omega t \leq \frac{\pi}{2} \end{array} \right. \quad (6)$$

The fundamental output voltage can be found by taking the Fourier component of the fundamental ( $n=1$ ) of the above describing function. The integration can be done over quarter cycle and the multiplied by  $\frac{4}{\pi}$  as before. Integrating over the different intervals. During the first interval, the relevant integral becomes

$$\int_0^{\frac{\pi}{6}} \left\{ \frac{3V_m}{2} \sin^2(\omega t) d\omega t = \frac{3V_m}{2} \left[ \frac{\pi}{12} - \frac{\sqrt{3}}{8} \right] \right\}$$

The relevant integral of the function during the second interval is

$$\int_{\frac{\pi}{6}}^{\alpha} \left\{ \frac{3}{4}V_m \sin(\omega t) + \frac{\sqrt{3}}{4}V_m \cos(\omega t) \right\} \sin(\omega t) d\omega t = \frac{3}{4}V_m \left[ \frac{\alpha}{2} - \frac{\pi}{12} - \frac{1}{4} \sin 2\alpha + \frac{\sqrt{3}}{8} \right] + \frac{\sqrt{3}V_m}{4} \left[ \frac{1}{8} - \frac{1}{4} \cos 2\alpha \right]$$

The integral over the third interval reduces to

$$\int_{\alpha}^{\frac{2\pi}{3}-\alpha} \sin(\omega t) d\omega t = \frac{3}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha$$

and the last integral becomes

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$$\int_{\frac{2\pi}{3}}^{\frac{\pi}{2}} \left\{ \frac{3}{4} V_m \sin(\omega t) + \frac{\sqrt{3}}{4} V_m \cos(\omega t) \right\} \sin(\omega t) d\omega t = \frac{3V_m}{4} \left[ \frac{\alpha}{2} - \frac{\pi}{12} - \frac{\sqrt{3}}{8} \cos 2\alpha + \frac{1}{8} \sin 2\alpha \right] + \dots$$

$$\dots \frac{\sqrt{3}V_m}{4} \left[ \frac{1}{4} - \frac{1}{8} \cos 2\alpha - \frac{\sqrt{3}}{8} \sin 2\alpha \right]$$

Summing up the different regions and multiplying by  $\frac{4}{\pi}$ , the magnitude of the output fundamental becomes

$$\frac{4}{\pi} \left\{ \frac{3V_m}{4} \left[ \alpha - \frac{\sqrt{3}}{4} \cos 2\alpha - \frac{1}{4} \sin 2\alpha \right] + \frac{3}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right\} \quad (7)$$

Increasing the modulation index further results in the value of  $\alpha$  reducing further, till, at one instant, the value of  $\alpha$  becoming exactly  $\frac{\pi}{6}$ . This point defines the end of OMR1 and the beginning of OMR2. The defining function from this point onward changes. The magnitude of the fundamental output at this transition region can be obtained by substituting the value of  $\alpha$  in either Eq.7 or Eq.12. The output fundamental (and the MI) evaluates to  $\frac{4}{\pi} \times \left[ \frac{\pi}{6} + \frac{\sqrt{3}}{4} \right] \approx 1.218$  Fig.7 shows an uncompensated reference of peak amplitude 1.218 and a compensated reference where the peak has been increased to  $\frac{4}{3}$  The mapping on the voltage space vector plane is shown in Fig.8(a).

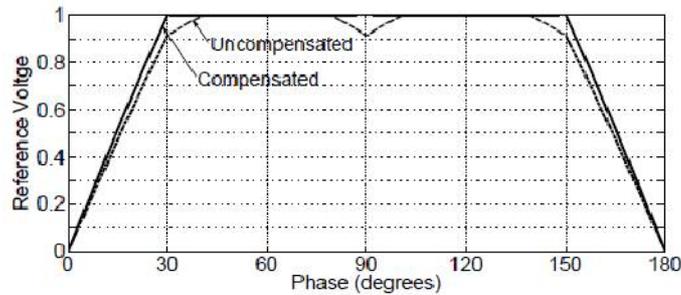
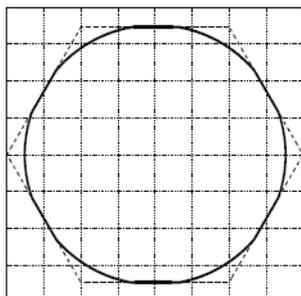
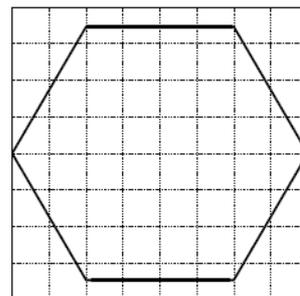


Fig. 7. Reference Voltage for MI=1.218

Over-modulation region 2: Increasing the modulation index further results in the vector being 'held' in one of the active states as there is an interval where both the extreme valued reference signals and the middle valued signal are at one or the other extremities for some duration of time.



(a) over-modulation region1 / Uncompensated with MI=1.218



(b) End of OMR1 and OMR2

Fig. 8. Locus output voltage vector in the voltage space vector plane



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This implies that a state is applied for several carrier cycles before it shifts to another state. Another important aspect is that there is no zero state being applied, as, the maximum and minimum valued signals are always at one of the opposite extremes. On the space vector plane, the trajectory this region of operation will be along the boundary of the hexagon as shown in Fig. 8(b). The fundamental component can be evaluated using the Fourier series as before, the function being defined by:

$$v_{ref} = \begin{cases} \frac{3}{2} V_m \sin(\omega t) & 0 \leq \omega t \leq \alpha \\ 1 & \alpha \leq \omega t \leq \frac{\pi}{2} \end{cases} \quad (8)$$

Evaluating the Fourier series of the above waveform for magnitude of the fundamental component yields

$$V_1 = \frac{4}{\pi} \left[ \int_0^\alpha \frac{3}{2} V_m \sin^2(\omega t) d\omega t + \int_\alpha^{\pi/2} \sin(\omega t) d\omega t \right] \quad (9)$$

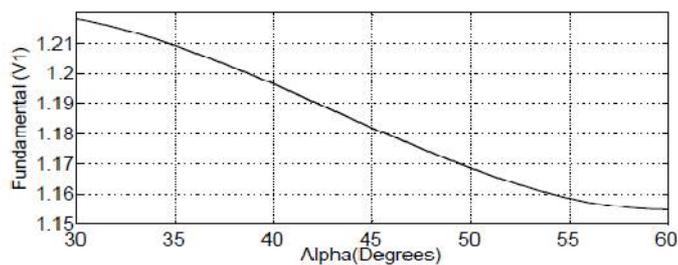
$$= \frac{4}{\pi} \left[ \frac{3}{2} V_m \left( \frac{\alpha}{2} - \frac{\sin 2\alpha}{4} \right) + \cos \alpha \right] \quad (10)$$

The value of  $\alpha$  can be determined from the intended voltage waveform as.  $\frac{3}{2} V_m \sin \alpha = 1$  (11)

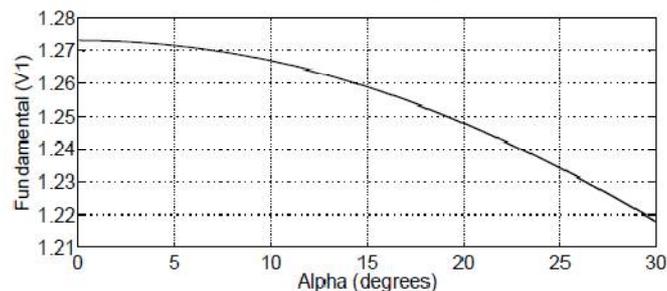
Substituting for  $V_m$  in the above equation, the magnitude of the fundamental component can be expressed as:

$$V_1 = \frac{2}{\pi} \left[ \frac{\alpha}{\sin \alpha} + \cos \alpha \right] \quad (12)$$

Fig.9(a) and (b) show the plots of variation of fundamental versus the angle alpha in over-modulation regions 1 and 2. The peak of the reference required for linear output of fundamental versus the output fundamental is shown in Fig.10 (a) and (b)



(a) Over-modulation region 1



(b) Over-modulation region 2

Fig. 9. Variation of output fundamental versus alpha

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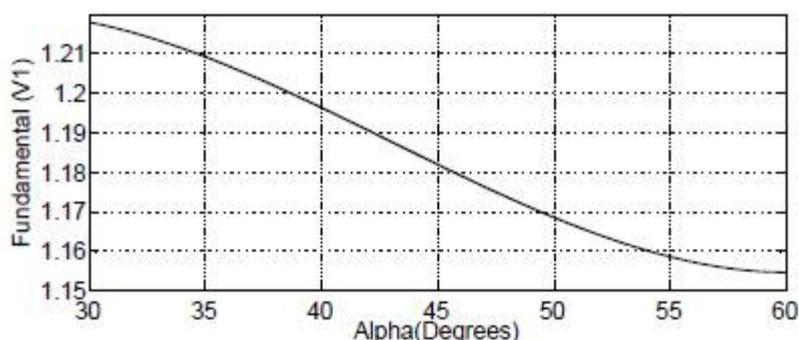
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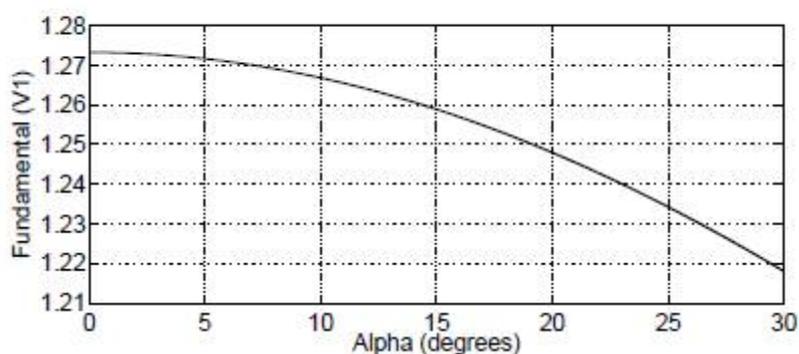
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## B. Time domain wave-forms in SVPWM

The wave-forms of the reference signals for the three phases in the three regions of modulation has the added advantage of providing information on the time duration for which the different states are applied. While the vector represented in the space phasorplane rotates with uniform angular velocity of  $\omega t$  radians per second in the linear and over-modulation region 1, the vector is held for some time at one of the six active states in over-modulation region 2.



(a) Over-modulation region 1



(b) Over-modulation region 2

Fig. 10. Peak phase reference versus peak output fundamental

The duration for which the vector is held at one of the active states depends on the modulation index, and will vary from zero at the beginning of region 2 to 60 degrees of phase angle equivalent in the six-step mode of operation. This holding duration cannot be represented in the space phasor plane as no information of time is available. However, the time domain wave forms will clearly indicate the duration for which the vectors are applied as seen in Fig.11.

## V. RESULTS

### A. Waveform generation

The algorithm was implemented in MATLAB-SIMULINK and the resulting three-phase reference signals that lead to linear modulation over the entire range of inverter output are shown. The modulating signals are plotted versus time for a 50 Hz output. Four sub-plots represent the three-phase modulating signals in four regions of operation, namely over-modulation region 1, end of over-modulation region 1, over-modulation region 2 and the end of over-modulation region 2 which is the six step mode. This can be correlated with Fig.8 where the different operating modes as visualized on the voltage space phasor plane. There are three different operating zones defined on the voltage space vector plane in the over-modulation region. When the magnitude of the extreme phases are less than unity, all three phases switch and the resultant average vector traces a circular trajectory. This is also seen over part of the cycle in OMR1. The time interval is indicated as Circular Trajectory Transit Interval (CTTI) in Fig.11(a). In OMR1, over certain parts of the cycle, the locus moves along the boundary of the hexagon. This happens when no zero state is applied wherein the extreme

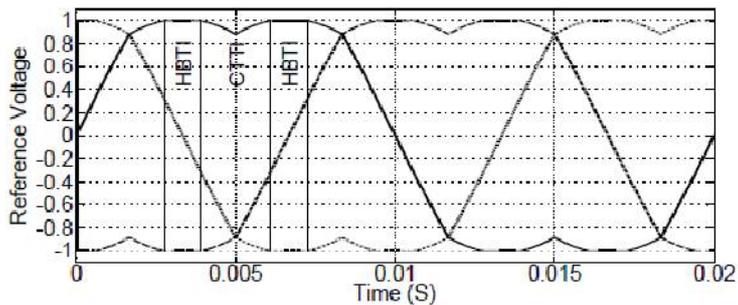
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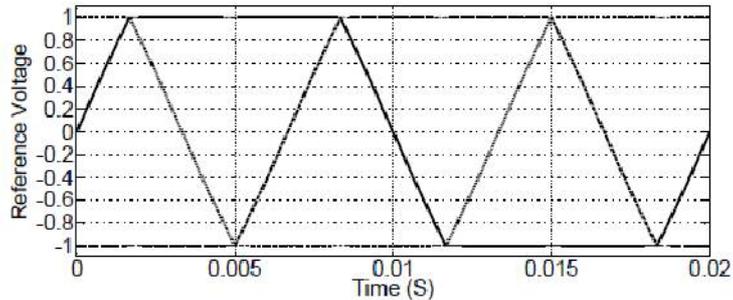
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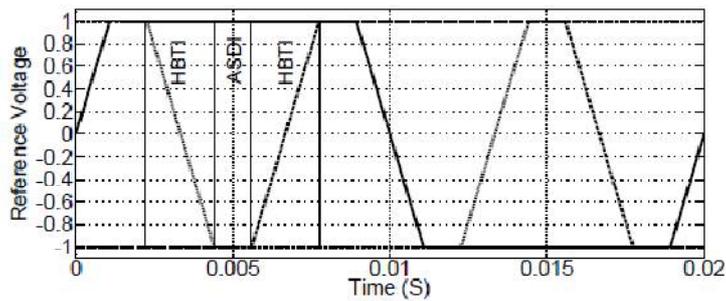
valued phases are always at unit magnitude, positive and negative. The middle valued phase switches, thereby applying adjacent active states. This interval on the time axis is indicated as Hexagonal Boundary Transit Interval (HBTI). At the end of OMR1 (modulation index 1.218), the locus of the vector is entirely along the hexagon boundary as the magnitude of the maximum and minimum reference phase signals are  $\pm 1$ . This mode is indicated in Fig.11 (b)



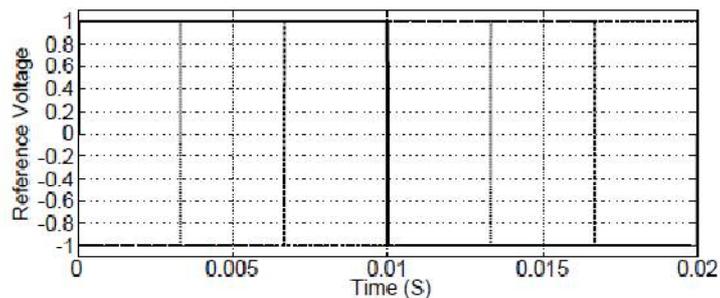
(a) Modulation index 1.18



(b) Modulation index 1.218



(c) Modulation index 1.25



(d) Modulation index  $\frac{4}{\pi}$

Fig. 11. Three-phase reference signals for different modulation indices



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As the reference is further increased, there exists an interval where an active vector is applied or 'held' for a certain interval before the HBTI. This interval is indicated as Active State Dwell Interval (ASDI) where-in all the three references are of unit positive or negative magnitude, and there is no middle valued phase that switches states in a carrier cycle. The average voltage vector applied over one switching cycle is one of the six active states and a zero state is not applied in this mode. This happens in OMR2 where a greater value of output fundamental is desired. Since the total time interval over a cycle remains fixed, the holding of an active state reduces the HBTI and this can be seen in Fig.11(c). This effect cannot be depicted on the space vector locus diagram as time information is not shown. As the modulation index is further increased, the ASDI increases at the expense of HBTI till, in the six step mode of operation, active states are applied for 60 degrees each giving the maximum possible fundamental output. This mode is depicted in Fig.11(d)

### B. Algorithm implementation

The algorithm described was implemented in generating the reference voltages in an open loop v/f control of an induction motor drive in order to verify its compatibility with the existing control scheme. A representative soft start implementation was utilized, and the output voltage generated for step change in speed reference as well as for reversal. It can be seen that for a step change in speed command to the maximum commanded speed, the reference smoothly transits to a square wave as expected. This transition is shown in Fig 11.

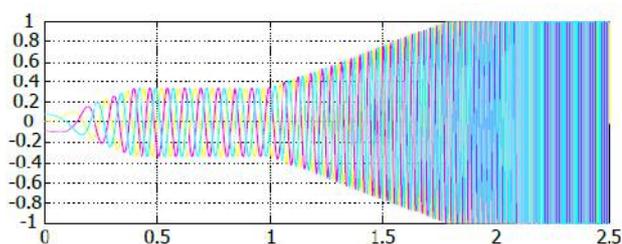


Fig. 12. Change in speed reference to maximum speed

The wave-forms for speed reversal in Fig.12 show the effect of the soft start circuit in preventing any sudden change in reference voltages.

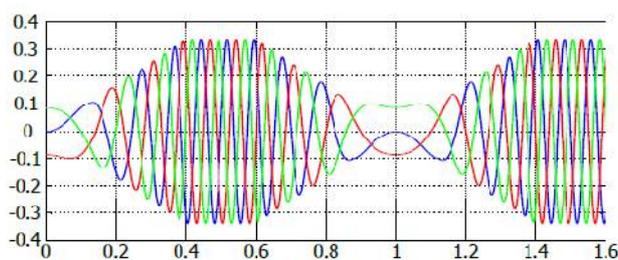


Fig. 13. Speed reversal

## VI. CONCLUSIONS

An algorithm for modifying the magnitude of the three-phase reference voltages in carrier based space vector pulse width modulation is introduced, that enables linear variation of the fundamental component of the output voltage of an inverter over the entire range of modulation. The implementation can be either as a real time calculation based on the formula, or a predefined look-up-table can be used for processors with lower resources. This algorithm can be



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employed for volts/hertz control as well as vector control of induction motors where the instantaneous values of reference signals are used to generate the switching states. It is applicable for both two level and also multi-level inverters. The implementation is easier than calculation of state timings since the need for evaluating operation in over-modulation region and subsequent recalculation of switching times can be avoided in this scheme.

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