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# A Comparative Study of Modulation Schemes for Cyclo-Inverters



**Abstract**— Three modulation techniques namely Sinusoidal PWM, Space Vector PWM and Delta Modulation have been applied in cyclo-inverter for reducing harmonics in the output. It has been found that for Sine PWM, for modulation index,  $m$ , around 0.5 to 1, the minimum total harmonic distortion factor (THD) obtained is 10 %. The harmonic contents in the cyclo-inverter output gradually increase when  $m$  is less than 0.5. Cyclo-inverter output improves for delta modulation scheme where the total harmonic distortion is found to be 4% when modulation index is lying from 0.75 to 1.5. Any further increase or decrease in modulation index increases the harmonics in cyclo-inverter. Similarly, for Space Vector PWM, THD has been also found to be as low as 5%. Since Delta modulation can be smoothly tuned to the designer's priorities and varying operating conditions by simple parametric adjustments, without any modifications of the timing structure it is recommended in cyclo-inverters as compared to Sinusoidal PWM and Space vector PWM both in terms of switching losses as well as harmonic reduction.

**Keywords** – Delta Modulation, Space Vector Modulation, Cyclo-Inverter, Harmonic Reduction, Total harmonic distortion

## I. INTRODUCTION

Cyclo-inverters are ideal for high frequency induction heating, arc welding and plasma generation, power factor correction, industrial laser drivers and so on [1-2]. Eventual applications could range from power grid stabilizers to ion rocket drives. A unique advantage of load-commutated cyclo-inverter [3] is that device-switching loss is eliminated and therefore, the inverter can operate at high frequency with high efficiency. One of the main disadvantages with this circuit is however, that high rating commutating components are required as they carry the load current continuously. A direct AC-to-AC converter has been designed in [4], which uses self-commutated devices and eliminates the need for external commutation circuit. The output of cyclo-inverter is however rich in harmonics.

The conventional methods of filter [5] cannot be used for reduction of harmonics in cyclo-inverter as the output frequency is varying and using tuned filter for each harmonic is not feasible. Various Modulation Techniques are employed [6] to improve the quality of load voltage. They may be classified as i) Carrier Based PWM, and ii) Non Carrier Based PWM. While Sinusoidal PWM and Delta Modulation are typical examples of the former technique [7], Space Vector Modulation is the example of the latter [8]. Although these techniques have been successfully implemented for a wide range of application but still it is not clear which of these technique would be better in terms of control circuitry and for offering a sinusoidal output with low harmonic contents when applied to cyclo-inverters. In this paper a comparative study has been made for these three

techniques to obtain the performance in terms of load voltage and total voltage distortion associated with filters.

## II. MODULATION TECHNIQUES

Fig. 1 shows the basic circuit of a cyclo-inverter consisting of a positive converter PC and a negative converter NC both connected in anti parallel. The output is obtained through proper conduction of IGBTs in the two input cycles. The output frequency of the converter,  $f_o$  is  $f_i \times N_r$  where  $N_r$  is an integer and  $f_i$  is the source frequency. In order to optimize the harmonics and to improve the output of cyclo-inverter, gate pulses to different IGBTs are modulated using three modulation techniques: 1) Sinusoidal PWM, 2) Space Vector PWM and 3) Delta Modulation and their performance is compared in terms of total harmonic distortion in the output.

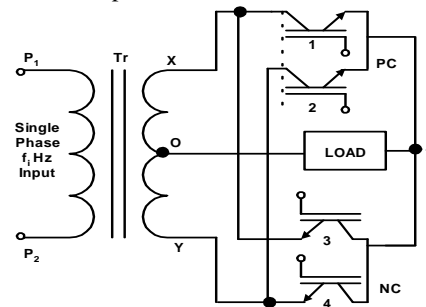


Fig. 1 IGBT Based Cyclo Inverter

### A. Sinusoidal PWM

In Sine PWM [9] the switching instants are decided by the points of intersection of a high frequency triangular wave called as carrier wave and a reference sine wave at the frequency of the required fundamental output voltage. Gating signals are generated at the instants when sinusoidal output is high than triangular wave. The unidirectional triangular carrier wave consists of  $n$  triangular pulses in each half

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cycle, where  $n \geq N_r$ . The relevant circuit is as shown in the Fig. 2

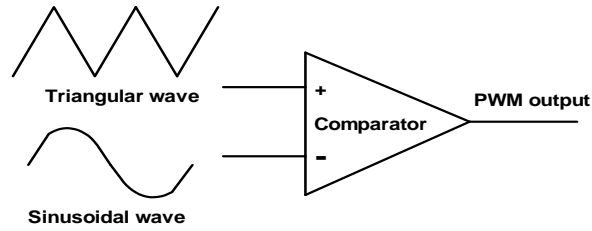


Fig. 2. Circuit diagram to produce modulated signal

The logical gating pulses for a particular  $N_r$  to the four IGBTs [4] of the proposed cyclo-inverter are ANDed with the logical SPWM output and the resulting pulses, after amplification to the required gating power level, are fed to the respective IGBTs. The output voltage produced by the cyclo-inverter contains the fundamental component of which the sine wave is a replica. In addition, it contains harmonic components which are located in bands around multiples of the triangle frequency.

**B. Space Vector PWM**

The space vector PWM (SVM) method is based on the space vector representation of the voltages in the  $\alpha, \beta$  planes. The  $\alpha, \beta$  components are found by park transform, where the total power, as well as the impedances, remains unchanged.

The control concept of SVM for a single-phase case is much similar to that for three phases. In three phases, Park transformation is used to transfer the interaction effects of different phases on each other to the fixed  $\alpha$  and  $\beta$  stationary reference frame. However in the single phase case the analysis can be done in the same  $\alpha$  and  $\beta$  stationary reference frame with out the need for any special transformation. This method is generally used for PWM modulation of inverters [10].

Equation (1) gives the space voltage vectors for an inverter, using the space vector modulation technique [11]

$$[V_1 \ V_2]^T = (1/2) U_{dc} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} [a \ b]^T \quad (1)$$

Where  $[V_1 \ V_2]^T$  = voltage space vector

$U_{dc}$  = The dc link voltage

$[a \ b]^T$  = switching state vector,

Here each a and b can have values as either '0' or '1'. A zero value denotes that the switches  $T_1$  &  $T_3$  are conducting whereas one value denotes that the switches  $T_2$  and  $T_4$  are conducting. In case of a cyclo-inverter, there are four switches arranged in pairs of two as shown in Fig. 1

During the positive half cycle the switches  $T_1$  and  $T_4$  are forward biased and  $T_1$  gives positive output during positive half cycle and  $T_4$  gives negative output. During the negative half cycle, similarly, switches  $T_2$  and  $T_3$  are forward biased,  $T_2$  giving positive output and  $T_3$  giving negative output. Thus at any given time during the operation of the cyclo-inverter at the most one switch can be ON. During each cycle, there are periods when no switch is conducting. Thus the switching states can be summarized in table 1. The state

vector equations for the positive and negative converters are given by (2) and (3) respectively

For positive converter

$$[V_1 \ V_2]^T = (1/2) V_{ac} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [a \ b]^T \quad (2)$$

For negative converter

$$[V_1' \ V_2']^T = (1/2) V_{ac} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} [a \ b]^T \quad (3)$$

TABLE 1: SWITCHING STATES OF CYCLO-INVERTER

Positive Converter				Negative Converter			
State	ON devices	$V_{out}$	Space Voltage Vector	State	ON devices	$V_{out}$	Space Voltage Vector
0	$T_1$	$V_1 = V_{ac}/2$	[1 0]	0	$T_3$	$V_1' = -V_{ac}/2$	[1 0]
1	$T_4$	$V_2 = -V_{ac}/2$	[0 1]	1	$T_2$	$V_2' = V_{ac}/2$	[0 1]
2	--	0	[0 0]	2	--	0	[0 0]
3	$T_1, T_4$	Not possible	[1 1]	3	$T_2, T_3$	Not possible	[1 1]

The space vector diagrams shown in Fig. 3 show the space vector representations for the Positive Converter state vectors and the Negative Converter state vectors

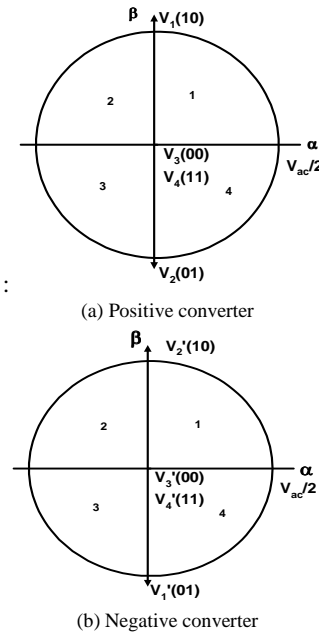


Fig. 3 Space Vector representation of cyclo-inverter

Thus it is apparent that there are only two active and two zero voltage space vectors. The adjacent space vectors are combined with appropriate timing in order to provide an average output voltage during each switching period, which follows the reference voltage  $V_{ref}$ . The output voltage is created through the addition of two vectors  $(t_1/t_x) V_1$  and  $(t_2/t_x) V_2$  where  $t_x = 1/2 * f_s$  and  $f_s$  is the switching frequency.

Fig. 4 shows a schematic timing sequence required for switching the IGBTs in the positive half cycle. Here  $t_1$  denotes the time for which the IGBT  $T_1$  is ON,  $t_4$  denotes the time for which the IGBT  $T_4$  is ON and  $t_0$  is the time when no switch is ON.

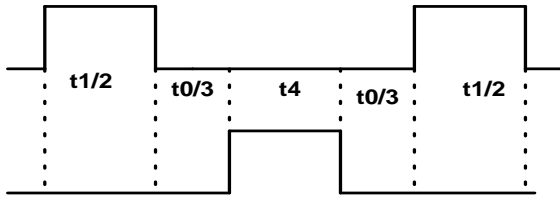


Fig. 4. Timing sequence of switching state for positive half cycle

Thus,  $t_1 + t_4 + t_0 =$  positive  $\frac{1}{2}$  cycle of the output at the desired output frequency. Similarly in the negative half cycle

$t_2 + t_3 + t_0 =$  negative  $\frac{1}{2}$  cycle of the output at the desired output frequency.

Thus integrating over half a switching period the time durations for each voltage state is calculated as follows: (taking  $t_4 = k.t_1$ )

$$\int_0^{t_x} V_{ref} dt = \int_0^{u_1} V_1 dt + \int_{u_1}^{u_2} V_2 dt + \int_{u_3}^{u_4} V_1 dt \quad (4)$$

Where

$$\begin{aligned} u_1 &= tx/3 + t_1/6 - k.t_1/3 \\ u_2 &= u_1 + k.t_1 \\ u_3 &= u_2 + tx/3 - (1+k).t_1/3 \\ u_4 &= u_3 + t_1/2 \end{aligned}$$

Solving (4) (for say, output frequency = 150 Hz ),

$$\begin{aligned} 2 \int_0^{t_x} 12\sqrt{2} \sin(300\pi t) dt &= 2 \int_0^{t_1/2} 12\sqrt{2} \sin(100\pi t) dt \\ + \int_{u_1}^{u_2} -12\sqrt{2} \sin(100\pi t) dt &+ \int_{u_3}^{u_4} 12\sqrt{2} \sin(100\pi t) dt \end{aligned} \quad (5)$$

Thus,  $t_1$  for this particular case can be obtained by solving the following equation for  $t_1$ :

$$\begin{aligned} 1 - \cos(50\pi t_1) + \cos(100\pi u_2) - \cos(100\pi u_1) + \cos(100\pi u_3) \\ - \cos(100\pi u_4) - (2/3)(1 - \cos(300\pi t_x)) = 0 \end{aligned} \quad (6)$$

Solving (6) the timings required for each voltage state, for a specified value of switching frequency and the constant  $k$  is obtained and hence the switching sequence is implicitly known. Next these switching sequences are used to give the exact duration pulses as gate signals to the IGBTs. Varying the values of  $k$  and switching frequency  $f_s$  may improve harmonic reduction

### C Delta Modulation Technique

Delta modulation, consisting of a forward comparator and a feedback filter, as shown in Fig. 5, utilizes a sine reference wave  $V_R$  and a delta shaped carrier wave  $V_F$ . The carrier wave  $V_F$  is allowed to oscillate within a defined window extending equally above and below the reference wave  $V_R$ .

The reference signal  $V_R$  is compared with carrier signal  $V_F$  obtained by integrating the comparator output signal to produce an error signal,  $e$ . The error signal,  $e$ , is quantized into one of two possible levels  $\pm E$  depending on its polarity, whereas the slope of reference signal determines the time duration between two successive levels. The comparator output is regularly sampled by the signal,  $f_c$  to produce the output binary pulses. Fig. 6(a), 6(b) and 6(c) show the waveforms at various nodes in the modulator block diagram.

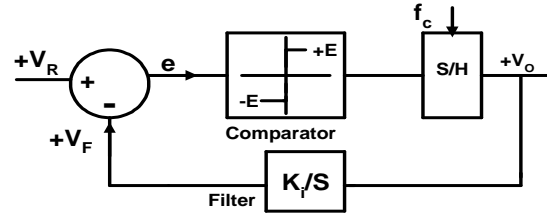
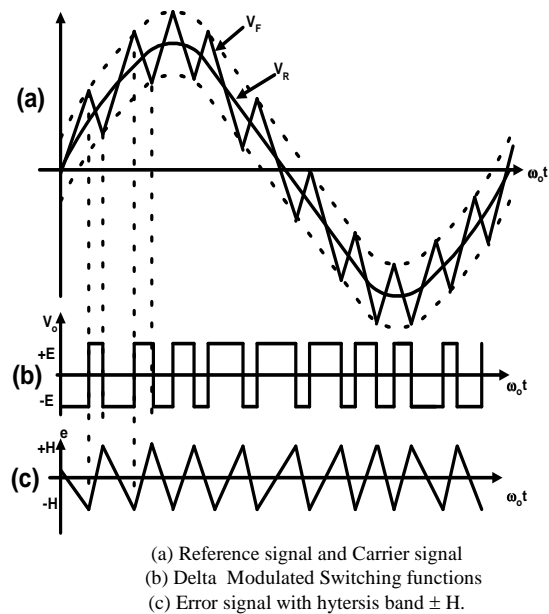


Fig. 5. Block Diagram of Delta Modulator



(a) Reference signal and Carrier signal  
(b) Delta Modulated Switching functions  
(c) Error signal with hysteresis band  $\pm H$ .

Fig.. 6. Delta Modulation Technique

The closed loop arrangement of the modulator ensures that the integrated output faithfully tracks the reference signal within the upper and lower boundary levels  $\pm H$ . It is however, important to note that as  $V_R$  increases in frequency, the component of  $V_o$  at that frequency also increases in amplitude. Thus the amplitude transfer characteristic of linear delta modulator demonstrates strong frequency dependence, [12] often undesirable in power electronic applications, where the demodulator, most frequently, is a simple low pass filter. Further examining operation of the linear delta modulator it is seen that in order to ensure that the feedback signal,  $V_F$ , tracks the reference, a slope overload condition must be satisfied. This requires that  $dV_R / dt$  should never exceed the maximum rate of change of  $V_F$ . Let

$$V_R = V_S \sin(\omega_o t) \quad (7)$$

$$\left[ \frac{dv_R}{dt} \right]_{\max} = V_s \omega_o \tag{8}$$

$$\left[ \frac{dv_F}{dt} \right]_{\max} = K_i V_o \tag{9}$$

where  $\omega_o$  is reference signal radian frequency,  $K_i$  is the integrator gain and  $V_o$  is output switching level. From (8) and (9)

$$V_s \omega_o \leq K_i V_o \tag{10}$$

From (10) it follows that a linear Delta modulator cannot encode high frequency sinusoidal signal without running into a slope overload condition, unless the input amplitude is restricted.

This interdependence of amplitude and frequency of the reference signal in the slope overload condition can be eliminated [13] by integrating the reference as shown in Fig. 7 Again for  $V_F$  to track  $V_R$  the maximum slope of  $V_R \leq$  maximum slope of  $V_F$ . Now

$$\begin{aligned} V_R &= K_i \int V_i dt = K_i \int V_s \sin(\omega_o t) dt \\ &= - \frac{K_i V_s}{\omega_o} \cos(\omega_o t) \end{aligned} \tag{11}$$

Hence, from slope overload condition

$$V_s \leq V_c \tag{12}$$

The slope overload condition is now independent of the reference frequency and amplitude transfer gain is seen to be unity, a very desirable attribute [10]. The same objective can be achieved by replacing, two integrators, in Fig. 7 with one integrators placed after the summing junction. This leads to unity feedback system with integrator [14] in the forward path as shown in Fig. 8.

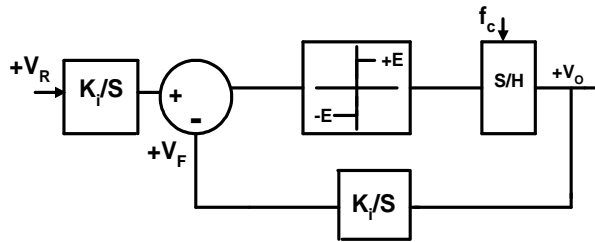


Fig. 7. Delta Modulator with integrator at Input

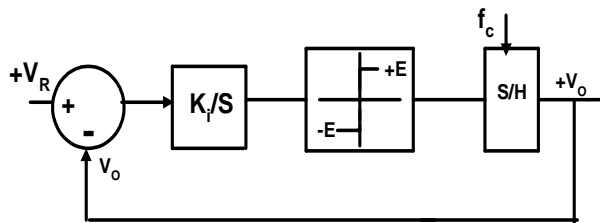


Fig. 8 Block Diagram of Sigma Delta Modulator

The integrator position results in substantially zero steady state error for any reference with a frequency much smaller than sampling frequency,  $f_c$ . This delta modulation scheme is

popularly known as Sigma delta modulation [15]. For a single phase cyclo-inverter a sine wave having desired output frequency, is the input to the modulator.

### III SIMULATION RESULTS

SIMULINK software and its facilities are used to model a cyclo-inverter loaded with inductive load. The results of simulation are reported for an output frequency of 150 Hz without and with modulation techniques. Fig. 9 shows the output waveforms and its total harmonic distortion for  $\omega_o = 150$  without applying any modulation technique. It is clearly seen that the output is rich in harmonics and THD is approximately 50%, which is highly undesirable.

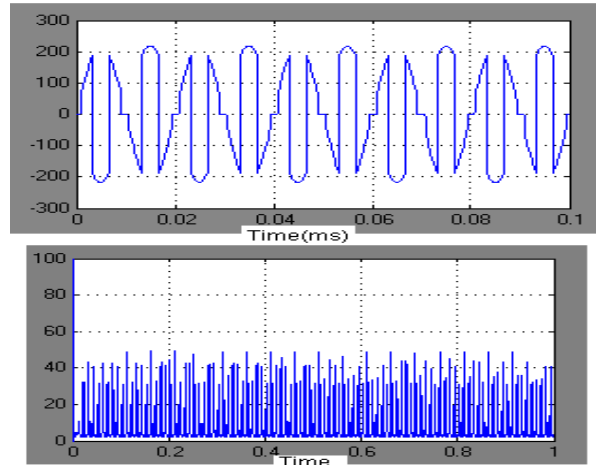


Fig 9. Output & THD of un-modulated Cyclo-Inverter

Fig. 10 shows the output waveforms of cyclo-inverter along with its total harmonic distortion when Sinusoidal PWM is implemented and modulation index  $m$  are taken as 0.25. It is observed that though the output contains harmonic but the THD is reduced to approximately 20% in this case.

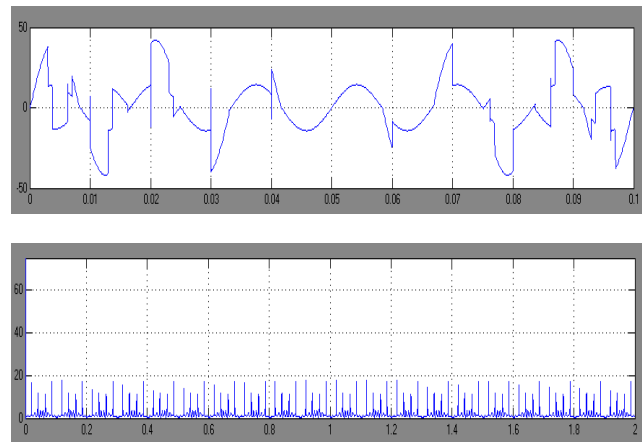


Fig. 10: Output & THD of cyclo-inverter with SPWM for  $m = 0.25$  &  $f_c = 300$  Hz

With further increase in  $m$ , the THD is decreasing and for  $m=1$  it is only 10% (Fig. 11).

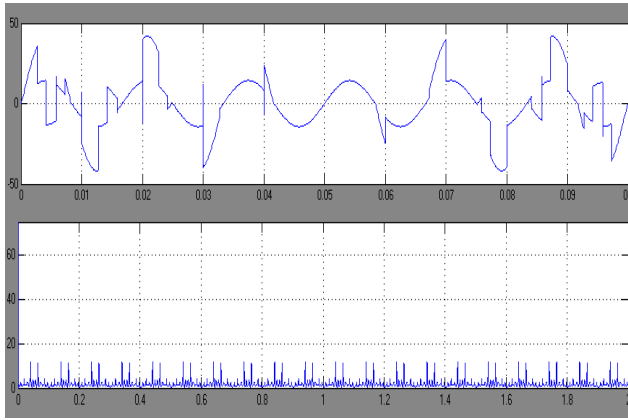


Fig. 11. Output & THD of cyclo-inverter with SPWM for  $m = 1$  &  $f_c = 300$  Hz

It may also be pointed out that if the switching frequency of the carrier wave is increased it affects the THD and reduces it. The frequency of the carrier wave is generally taken as 5 to 7 times the output frequency of cyclo-inverter. Fig. 12 shows the output waveform with sine PWM when switching frequency is increased to 1200 Hz.

Fig. 13 shows the output of cyclo-inverter when SVPWM is implemented with  $f_s = 1.2$  kHz and  $k = 0.5$ . It is shown that the THD in the output of the cyclo-inverter is approximately 28%.

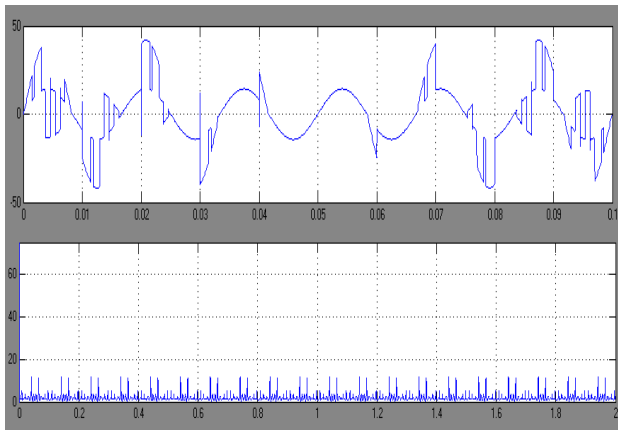


Fig. 12. Output & THD of cyclo-inverter with SPWM for  $m = 1$  &  $f_c = 1.2$  kHz

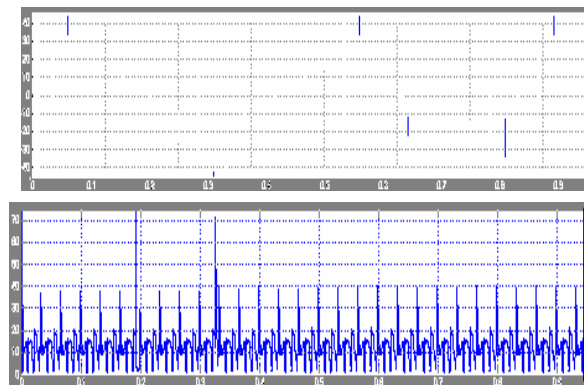


Fig. 13. Simulated Results with SVPWM for  $k = 0.5$  & switching frequency  $f_c = 1.2$  KHz

Fig. 14 shows the modulated output with SVPWM when  $f_s = 1.5$  kHz and  $k = 0.5$ . It is shown that now the THD in the output of the cyclo-inverter is reduced to 8%. With increase in switching frequency the THD may further be reduced to 5% as shown in Fig. 15 for  $f_s = 2$  kHz.

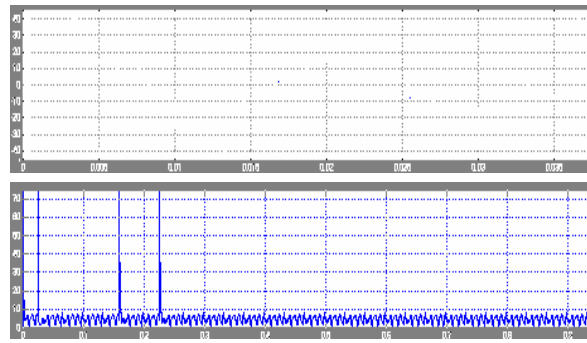


Fig. 14. Output & THD of cyclo-inverter with SVPWM for  $k = 0.5$  & switching frequency  $f = 1.5$  KHz

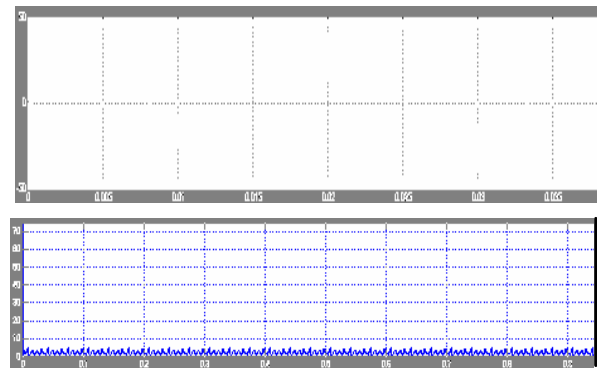


Fig. 15. Output & THD of cyclo-inverter with SVPWM for  $k = 0.5$  & switching frequency  $f = 2$  kHz

Fig. 16 and 17 show the results when switching frequency  $f = 2$  kHz and  $k$  is varied from 0.1 to 0.75. For  $f = 2$  kHz, least harmonic output is obtained for  $k$  in the range of 0.5 to 0.75. THD of the output also improves in this case as compared to SPWM with as minimum as 5%. Fig. 18 shows the output waveform along with its total harmonic distortion when Delta modulation is implemented and modulation index  $m$  is taken as 0.5. THD in this case is found to approximately 25%.

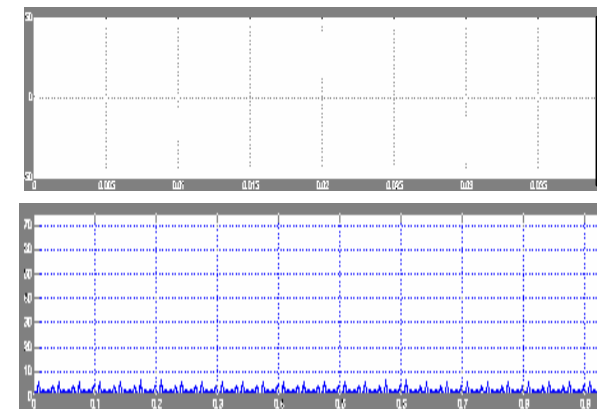


Fig. 16. Output & THD of cyclo-inverter with SVPWM for  $k = 0.5$  & switching frequency  $f_c = 2$  kHz

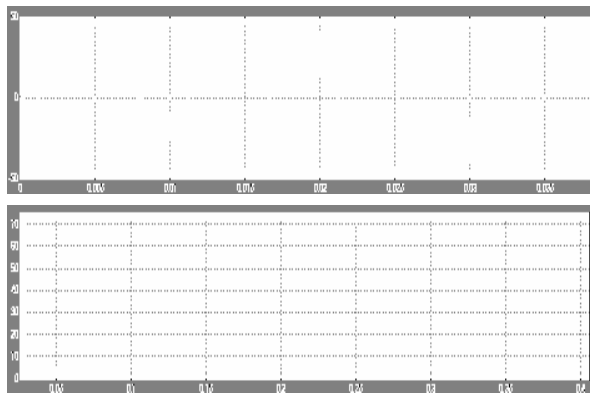


Fig. 17 Output & THD of cyclo-inverter with SVPWM for  $k = 0.75$  and switching frequency  $f_c = 2$  kHz

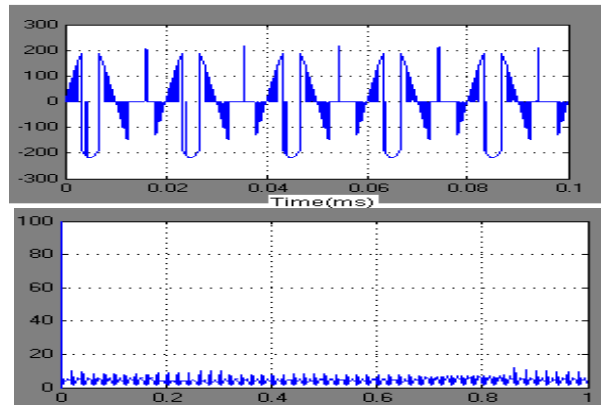


Fig.20. Output & THD of Cyclo-inverter with DM for  $m=1$  &  $f_c = 2$  kHz

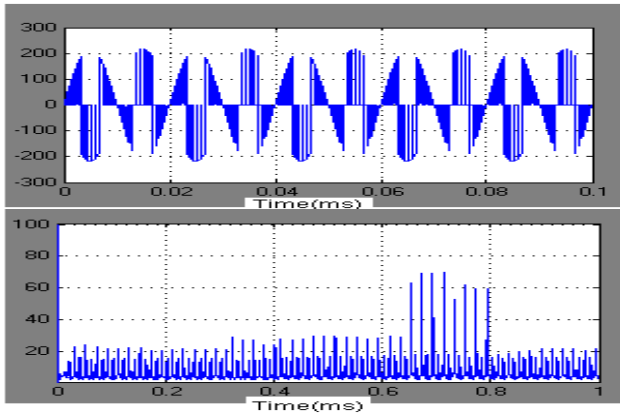


Fig 18 Output & THD of Cyclo-inverter with DM for  $m = 0.5$  &  $f_c = 2$  kHz

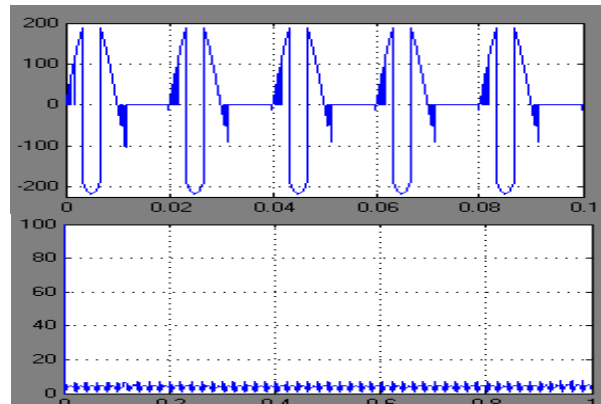


Fig.21 Output & THD of Cyclo-inverter with DM for  $m = 1.33$  &  $f_c = 2$  kHz

When  $m$  is increased and say taken as  $0.75$ , then the output though contain harmonic but the THD is reduced to approximately  $8\%$  as shown in Fig. 19. With further increase in  $m$ , THD decreases and it is  $7\%$  for  $m= 1$  shown in Fig. 20. When  $m$  is increased beyond one that is for over modulation case, say,  $m =1.33$ , THD further reduces to approximately  $5\%$  (Fig. 21). With further increase in  $m$ , say  $m =2$ , THD again starts increasing and reaches to  $12\%$  (Fig. 22).

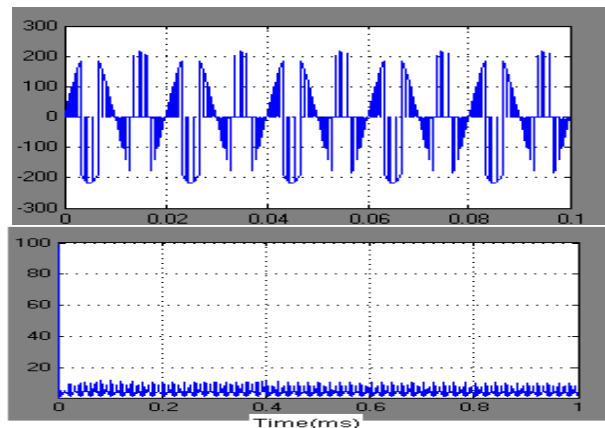


Fig. 19 Output & THD of Cyclo-inverter with DM for  $m = 0.75$  &  $f_c = 2$  kHz

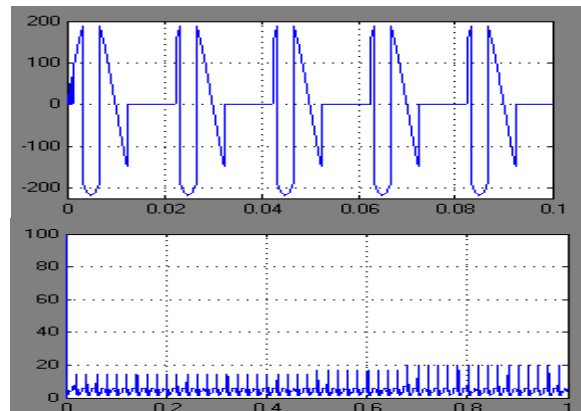


Fig. 22 Output & THD of Cyclo-inverter with DM for  $m = 2$  &  $f_c = 2$  kHz

#### IV. CONCLUSIONS

Three modulation techniques, Sine PWM, State Vector PWM and Delta modulation techniques have been implemented on cyclo-inverter in order to improve the output of the cyclo-inverter. It has been found that for Sine PWM, with increase in triangular carrier wave frequency, switching frequency increases, but the total harmonic distortion of the cyclo-inverter output does not reduce significantly. Switching losses increase proportionally with the carrier frequency.

THD is low for modulation index around 0.5 for constant carrier frequency. It increases abruptly at  $m$  around 0.75. Harmonic content of the cyclo-inverter output gradually increases with a decrease in  $m$  below 0.5. The technique of SPWM fails for  $m > 1$  (i.e. over modulation is not possible in SPWM). Lowest THD obtained with this technique is 10 %.

In state vector PWM, since the switching frequency can be specified in advance, therefore switching losses can be controlled easily. Cyclo-inverter output and its THD improves with increase in frequency in the range 1.2 KHz to 2.2 KHz and  $k=0.5$ . For  $f = 2$  KHz, least harmonic output is obtained for  $k$  in the range of 0.5 to 0.75. THD of the output also improves in this case as compared to SPWM with as minimum as 5%.

For delta modulation, with an increase in the carrier frequency above 2 KHz, THD reduces but not significantly. THD is low for modulation index,  $m$  lying in the range of 0.75 to 1.5 Any further increase or decrease in  $m$ , increases the harmonics in cyclo-inverter. The minimum THD found in this case is 4% only.

Thus, out of these three techniques, Space vector modulation and delta modulation technique both may be proposed for cyclo-inverter. Since delta modulation technique enjoys the performance figures [16] that are close to and in some regions even better than-the commonly accepted SVPWM algorithm. A very valuable property of Delta modulation not shared by the SVPWM is that it can be smoothly tuned to the designer's priorities and varying operating conditions by simple parametric adjustments, without any modifications of the timing structure. Other assets include the freedom from minimum pulse width problems relaxed hardware requirements and reduced dead-time distortion in the lower voltage range. Thus, the Delta modulation can prove very useful as a complementary idea for the control of cyclo-inverter.

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